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DESIGN, PRODUCTION AND EVALUATION OF IMPROVED CAST SHELL ALLOYS USING MATHEMATICAL MODELS

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INTERIM REPORT
February 17, 1966 - November 15, 1967

by

John Zotos

June 28, 1968

Department of Mechanical Engineering
Northeastern University
360 Huntington Avenue
Boston, Massachusetts 02115

Contract No. DA-19-066-AMC-00317 (X)

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
WATERTOWN, MASSACHUSETTS 02172

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ABSTRACT

This investigation attempts to implement a scientific analysis of factors affecting the properties of cast shells, design some improved cast shell alloys, and suggest how to produce these new products.

Incomplete fragmentation data resulted in the redirection of this project towards an implementation of a scientific analysis of factors affecting the mechanical properties of ductile cast iron alloys.

Two series of mathematical models are evaluated, i.e., Series 1, based on microstructural data and Series 2, based on alloy content data. Only the last four (4) of the eighteen (18) equations generated are significant at the 0.001 confidence level, or less, and seventeen (17) out of the twenty-four (24) independent, elemental variable (71%) are in agreement with metallurgical theory.

Since this investigation was based on a limited number of data sets, it is recommended that it be continued and expanded in the near future.

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I. INTRODUCTION

I. A. Preface

An examination of the metallurgical literature indicates that current cast shell compositions and processing procedures have been developed empirically, rather than in a scientific manner. This situation has yielded variable fragmentation results and has clouded the direction of future investigations due to the availability of too many uncertain, non-reproducible cast shell properties. It is evident, therefore, that a more scientific, analytical approach should be initiated immediately towards developing the desired cast shell alloys having reproducible properties. This is the aim of the study presented in this report.

I. B. Objective

This investigation attempts to implement a scientific analysis of factors affecting the properties of cast shells, develop a series of mathematical models which predict the desired properties of these cast shells, and in association with the Army Materials and Mechanics Research Center, design, produce and evaluate the improved cast shell alloys.

I. C. General Procedure

There are several steps required in the scientific development of improved cast shell alloys, namely:

1. Evaluate the variables affecting the properties of cast shells such as casting history, section size, grain size, thermal history, and alloy content.

2. Develop statistical models or equations which show the contributions of each of these variables towards the magnitudes of properties exhibited by the cast shells.

3. Analyze the metallurgical and statistical significance, and validity of the developed models in predicting properties.

4. Design an improved cast shell alloy composition and process history which should exhibit improved properties.

5. Produce the newly designed cast shell alloy in agreement with the prescribed process history.

6. Test the developed cast shell alloy and assess its level of attainment of design objectives.

7. Redevelop new statistical models using the new data and repeat steps 3, 4, 5, and 6.

Research being conducted at Northeastern University has indicated the significance of this scientific approach towards the development of improved cast metal alloys having predictable chemical, mechanical and physical properties.[1, 2, 3, 4, 5, 6]

II. STATISTICAL METHODS

II. A. Linear Regression System

Given a set of independent values (chemical composition and process variables) and a corresponding set of dependent values (mechanical properties) it is desired to find some functional form which will relate the dependent values to their independent values. The main approach in this study was to select a linear relationship as the functional form.

A linear equation explicitly defining the mechanical property was used of the form,

$$\text{Mechanical Property} = A + B\ (\%X_1) + C\ (\%\ X_2) + \ldots$$

where A is a pure constant used to adjust the hypersurface to the proper range of inspection of the nodular cast iron's mechanical property. This constant is the mean value of the iron mechanical property minus the sum of the products of the means of the independent variables with their respective coefficients. B, C, D,...are net regression coefficients (sometimes called partial regression coefficients), so called since they indicate the average change observed in the mechanical property due to a unit change of their respective independent variable while holding all other variables constant.

To find the constants A, B, C, D,.., which will position a hypersurface so that the optimum correlation between computed and observed results is achieved, a multiple linear regression system (least squares method) is used. The solution by the least squares method for a system with several independent variables would become prohibitively lengthy for hand calculation, therefore, a computer program was used to perform the desired calculations.

The utilization of linear relationships has its faults. The linear equation assumes that an increase in the value of the independent variable necessarily indicates a corresponding increase in the dependent variable regardless of the indication of any possible discontinuity or new phase formation in the metal system, and the so-called "principle of diminishing returns" is prohibited.

The regression equations can be justified only within the range specified by the observations used to derive the equation, cannot reflect any phenomena that might occur outside the inspected range. However, it can be assumed that the functional relationships between the chemical compositions of an alloy system, the process variables and the resultant mechanical property is a continuous one and some extrapolation beyond the observed range may be permitted with some degree of accuracy. A priori knowledge of the metal system then can justify some extrapolation of the regression equation beyond the observed range. The range of application of the data used for the derivation of each equation in this report is tabulated as is the arithmetic mean values of each variable. The total alloy content of the system is also given and any analysis of a system with alloy content exceeding this maximum will be an extrapolation beyond the intended range.

II. B. Statistical Parameters

II. B. 1. Validity of Equations

When an equation is derived by a regression system it must be justified as to its reliability and analyzed for its accuracy of estimate and its correlation with the given data. To accomplish this analysis, several statistical parameters are used.

These parameters are (1) the standard error of estimate (σ_e), (2) the coefficient of multiple correlation (R) and (3) the "F ratio". These statistical indicators can be used to show how closely the estimated values of the mechanical property can be expected to agree with the actual values, and what portion of the variance has been left unexplained. An indication is also given as to which dependent variables are most poorly represented by assuming a linear relationship. The statistical meaning of each parameter will now be discussed, and statistical references should be sought for formulas for each of these parameters.

The standard error of estimate (σ_e), sometimes called the standard deviation of estimate, is used to attain a measure of how closely the calculated estimate of the dependent variable agrees with the actual value. σ_e has the units of the mechanical property and indicates that 68.26 percent of the calculations performed using the regression equation and the given observations will have an error under the value of σ_e. The maximum error in prediction 95.44 percent of the time is $2\sigma_e$. This is based on the assumption that the observed data has a normal distribution. This assumption is the basic assumption used in statistical analysis and can be assumed valid for a random population with over 100 degrees of freedom.

The coefficient of multiple correlation (R) is the ratio of the standard deviation of the estimated values to the standard deviation of the original values. It indicates the relative importance of all the variables combined in predicting the dependent variable. It is, in essence, a measure of the closeness of fit of the observable data to the regression equation, where the value 1.0 indicates perfect correlation, while 0.0 indicates no correlation. The square of the coefficient (R^2) is the percentage indicating what portion of the variation of the mechanical property has been explained by the variation of the independent variables. ($1-R^2$) is the percentage of the variation left unexplained. For example, $R^2 = 0.8$ would indicate that 80 percent of the variation of the mechanical property has been successfully explained by the independent variables, whereas 20 percent of the variation has been left unexplained. This unexplained variation presumably is caused by unobserved residual elements or other variables that were neglected in this study.

The "F-ratio" is a reliability parameter attributing a level of significance to the equation. If the "F-ratio" yields a significance level below 5 percent, the results are acceptable to a statistician. A level of significance of 5 percent or below, indicates that the probability is one out of twenty that the results obtained were achieved purely by chance. Any significance level higher than 5 percent indicates that the probability that the results occurred by chance is high, and that the observations used to generate the regression equations were not drawn from the same source, and therefore, have a low correlation.

The degrees of freedom (D. of F.) illustrate the excess amount of data points available to be used in the regression equation and as the degrees of freedom increase, the accuracy of the results increase. There is, however, an economical limit above which a further increase in the degrees of freedom yields a lesser increase in accuracy. One hundred degrees of freedom and over is considered a respectable number for a regression system. As an example of determining the degrees of freedom, assume that an equation has two unknown constants. To solve for these unknowns, two conditions are needed; if, however, 10 conditions are available, there is an excess of eight conditions, therefore, the system has eight degrees of freedom.

The above statistical parameters are tabulated for each equation generated and proper conclusions are drawn. The level of significance (L. of S.) based on the "F-ratio" criteria is recorded.

II. B. 2. Qualitative and Quantitative Analysis of Equations

Once the validity of the equations has been established, quantitative and qualitative methods of analysis are presented and analyzed. To find the qualitative effect of the independent variables on the dependent variables simply inspect the signs of the constants (net regression coefficients). If a positive constant is associated with a particular variable then the equation infers that a positive addition of the variable will increase the value of the mechanical property. Likewise, the addition of negative contributors will decrease the iron's mechanical property.

These equations are unique in that they provide quantitative as well as qualitative results. The mean contribution of each variable is found and compared to other elements, to indicate which variable is the most effective contributor for increasing the value of the mechanical property and which is the least effective. Some tables and graphs are provided for the most significant equations developed, indicating the following parameters: (1) The mean contribution of each variable is the product of the arithmetic mean value of the variable as previously tabulated and the associated net regression coefficient. (2) The percent contribution of each variable toward an increase in the mechanical property is simply the ratio of the products to the sum of the products plus the pure constant term. Note, at this point, that the constant term is given these equations to compensate for the effect of the base metal and neglected variables. Mathematically, this term prevents the regression line from going through the origin when all the variables are deleted. It could not be expected, however, that a deletion of all the elements would yield a mechanical property for iron since the equation has not been developed for inspection in this range and is therefore invalid.

The unit increase in the mechanical property for a nominal unit addition of each variable can also be determined. The unit increase can be determined by inspection of the coefficient of each independent variable. However, this parameter should be used only as a rough guess as to the effect of the variable, since the parameter is independent of the other variables, whereas, it is known that the independent variables are highly interrelated. Proper conclusions from the above two parameters are given after the presentation of the tabulated results for each equation.

After the qualitative and quantitative results are established and discussed, a general conclusion as to the validity and predictability of the equation as well as its agreement with known experimental results is presented.

III. DESCRIPTION OF DATA

III. A. Initial Literature Survey

The initial effort was directed towards a complete literature survey to obtain reliable cast shell fragmentation and mechanical property data for a variety of alloys such as gray, malleable and nodular irons and hyper-eutectoid steels, derived from:

a. a known casting history;

b. a known section size;

c. a known thermal history; and

d. a known alloy content.

A review of several hundred technical reports on the subject matter resulted in the segregation of twenty-eight (28) significant papers which contained a variety of data. Each of these twenty-eight reports was further examined to determine the specific listing of the following information:

a. fragmentation data, i.e., the mass distribution of the particles after a test blast;

b. section size of the cast shell;

c. alloy content;

d. grain size;

e. microstructural characteristics;

f. thermal history; and

g. mechanical properties such as Modulus of Elasticity, Tensile Strength, Yield Strength; Percent Elongation, Percent Reduction in Area; Impact Strength and Hardness.

Each of these twenty-eight reports were then classified as to which of the aforementioned properties were lacking in the reports furnished by the Army, so that the gaps existing in the available data could be filled in. Several attempts to fill gaps in the available cast shell fragmentation data ended in failure.

Since the fragmentation data search was only partially successful, part of the effort was directed towards a new objective, namely, to implement a scientific analysis of factors affecting the properties of ductile cast irons. Correlation of the mechanical properties of ductile cast irons with processing variables, microstructural variables, etc., then commenced.

III. B. Mechanical Property and Microstructural Data - Series 1

The series 1 data included mechanical property and microstructural results from several cast, ductile iron shells, produced by the Army.

The dependent mechanical property variables chosen were as follows:

1. Tensile Strength;
2. 0.2% Yield Strength;
3. Percent Elongation;
4. Percent Reduction in Area; and
5. Brinell Hardness Number.

The independent, microstructural variables chosen were quantitatively evaluated using various metallographic techniques and include:

1. Volume percent Graphite;
2. Volume percent Ferrite;
3. Volume percent Pearlite; and
4. Mean radius of the Graphite nodules.

Series 1A included only eight (8) complete data sets and the high, low and mean values of the qualifying dependent and independent variables are listed in Table 1.

TABLE 1 HIGH, LOW, AND MEAN VALUES
OF THE DEPENDENT AND INDEPENDENT VARIABLES
SERIES 1A

VARIABLE	HIGH	LOW	MEAN
TENSILE STRENGTH	112,800	55,000	76,444
YIELD STRENGTH (.2%)	71,500	37,750	50,919
PERCENT ELONGATION	19.5	2.3	10.7
PERCENT REDN. OF AREA	22.8	2.6	11.9
BRINELL HARDNESS	245	121	169
VOL. PERCENT CARBON	26.0	10.0	13.6
VOL. PERCENT PEARLITE	74.3	0.0	32.8
VOL. PERCENT FERRITE	90.0	14.5	53.6
GRAPHITE MEAN RADIUS	.001340	.000675	.000964

Total No. of Data Sets = 8

Series 1B included twelve (12) complete data sets and the high, low and mean values of the qualifying dependent and independent variables are listed in Table 2.

TABLE 2 HIGH, LOW, AND MEAN
VALUES OF THE DEPENDENT AND INDEPENDENT VARIABLES
SERIES 1B

VARIABLE	HIGH	LOW	MEAN
TENSILE STRENGTH	112,800	55,000	79,642
YIELD STRENGTH (.2%)	71,500	37,750	52,581
PERCENT ELONGATION	21.0	0.5	10.9
PERCENT REDN. IN AREA	23.7	0.9	11.8
BRINELL HARDNESS	245	121	176
VOL. PERCENT CARBON	26.0	5.9	12.0
VOL. PERCENT PEARLITE	76.7	0.0	33.3
VOL. PERCENT FERRITE	90.0	14.5	54.7
GRAPHITE MEAN RADIUS	.001340	.000428	.000834

Total No. of Data Sets = 12

III. C. Mechanical Property and Alloy Content Data - Series 2

The series 2 data included mechanical property and alloy content information from as-cast and normalized ductile cast iron alloys.[7]

The dependent mechanical property variables chosen were as follows:

1. Tensile Strength;
2. 0.2% Yield Strength;
3. Percent Elongation; and
4. Brinell Hardness Number.

The independent elemental variables included:

1. total percent carbon;

2. percent silicon;

3. percent manganese;

4. percent nickel;

5. percent molybdenum; and

6. percent magnesium.

The series 2A information was derived from as-cast specimens and included fifteen (15) complete data sets. The high, low and mean values of the qualifying dependent and independent variables are listed in Table 3.

TABLE 3 HIGH, LOW AND MEAN VALUES OF THE QUALIFYING DEPENDENT AND INDEPENDENT VARIABLES OF AS-CAST DATA - SERIES 2A

VARIABLE	HIGH	LOW	MEAN
ULTIMATE TENSILE STRENGTH	123,300	91,000	113,393
0.2% YIELD STRENGTH	87,500	70,800	77,213
PERCENT ELONGATION	4.8	0.8	3.606
BRINELL HARDNESS NO.	305	264	280
TOTAL CARBON	3.70	3.46	3.56
PERCENT SILICON	2.19	1.80	1.96
PERCENT MANGANESE	0.92	0.17	0.458
PERCENT NICKEL	2.58	0.62	1.766
PERCENT MOLYBDENUM	0.50	0.01	0.0426
PERCENT MAGNESIUM	0.073	0.042	0.0517

Total No. of Data Sets = 15

The series 2B information was obtained from normalized specimens and included thirteen (13) complete data sets. The high, low and mean values of the qualifying dependent and independent variables are listed in Table 4.

TABLE 4 HIGH, LOW AND MEAN VALUES OF THE QUALIFYING DEPENDENT AND INDEPENDENT VARIABLES OF AVERAGE - NORMALIZED DATA - SERIES 2B

VARIABLE	HIGH	LOW	MEAN
ULTIMATE TENSILE STRENGTH	138,600	125,500	130,775
0.2% YIELD STRENGTH	130,100	79,900	88,737
PERCENT ELONGATION	5.5	0.5	3.94
BRINELL HARDNESS NO.	390	284	301
TOTAL CARBON	3.70	3.46	3.56
PERCENT SILICON	2.19	1.80	1.96
PERCENT MANGANESE	0.92	0.17	0.458
PERCENT NICKEL	2.58	0.62	1.766
PERCENT MOLYBDENUM	0.50	0.01	0.0436
PERCENT MAGNESIUM	0.073	0.042	0.0517

Total No. of Data Sets = 13

IV. MECHANICAL PROPERTY MATHEMATICAL MODELS

IV. A. Series 1A Data

The initial computer analysis attempted to derive a multiple, linear regression model for each of the five (5) dependent mechanical properties as a function of all four (4) of the independent microstructural variables listed in Table 1. A total of five (5) equations or models were generated and had this general form:

MECHANICAL PROPERTY = A_0 + A_1 (Volume Percent Carbon) + A_2 (Volume Percent Pearlite) + A_3 (Volume Percent Ferrite) + A_4 (Graphite Mean Radius)

IV. A. 1. Linear Regression Models

All five (5) equations were derived on the basis of only eight (8) sets of data (See Table 1). Solving for the five (5) constants required by the general equation, i.e., A_0, A_1, A_2, A_3, and A_4, leaves only three (3) degrees of freedom for the regression analysis.

The initial five (5) models were generated to explain the variation in the ductile cast iron's tensile strength, 0.2% yield strength, percent elongation, percent reduction in area, and Brinell hardness number and are listed in Mathematical Model Set I. The correlation coefficient, i.e., R, and standard error of estimate, i.e., σ_e, are also listed for each of these equations. Within $\pm 1\sigma_e$, each equation can predict the mechanical property 68 percent of the time, and 95 percent of the time within $\pm 2\sigma_e$ of its mean value.

IV. A. 2. STATISTICAL SIGNIFICANCE

The level of significance of each equation and coefficient generated, i.e., α, was determined on the basis of the following parameters:

1. R - Correlation Coefficient
2. F - Ratio Calculated
3. t - Test Calculated
4. The Degrees of Freedom

In most cases, only those expressions or equations whose level of significance, i.e., α is 0.01 or less, should be considered worthy of discussion and significant. In addition, independent variables whose α values are 0.20 or less should be considered significant and analyzed further.

Based upon the values of R for equations 1-5 (see Mathematical Model Set I) and their associated degrees of freedom, F-ratio, etc., all five (5) models are significant at only the 0.1 confidence level.

Figures 1-5 illustrate the calculated vs. the experimental values of the ductile cast iron's dependent mechanical properties evaluated in equations 1-5. These graphs are called plotbacks and are actually visual representations of the correlation coefficients of each model generated.

In addition, Figures 6-10 identify the level of significance of each independent variable contained in equations 1-5. As shown in these figures, none of the individual coefficients were statistically significant below the 0.3 confidence level.

MATHEMATICAL MODEL SET I - SERIES 1A

EQUATIONS

TENSILE STRENGTH = +15,339 + 1,071 (Vol % C) + 903 (Vol % P)
+ 223 (Vol % Fe) + 6,648,900 (r)..............(1)

$R_{(1)} = 0.926$ $\sigma_{e_{(1)}} = 13{,}600$ psi

0.2% YIELD STRENGTH = -17,901 + 2,148 (Vol % C) + 844 (Vol % P)
+ 426 (Vol % Fe) - 8,608,800 ($\bar{r}$)...........(2)

$R_{(2)} = 0.920$ $\sigma_{e_{(2)}} = 9{,}100$

PERCENT ELONGATION = -28.84 + 1.534 (Vol % C) + 0.150 (Vol % P)
+ 0.303 (Vol % Fe) - 704.4 ($\bar{r}$)..............(3)

$R_{(3)} = 0.834$ $\sigma_{e_{(3)}} = 5.62$

PERCENT REDUCTION IN AREA = -33.33 + 1.998 (Vol % C) + 0.168 (Vol % P)
+ 0.332 (Vol % Fe) - 3,386 ($\bar{r}$).......(4)

$R_{(4)} = 0.901$ $\sigma_{e_{(4)}} = 4.91$

BRINELL HARDNESS NUMBER = 317.3 - 9.40 (Vol % C) - 0.316 (Vol % P)
- 1.62 (Vol % Fe) + 68,787 ($\bar{r}$)..............(5)

$R_{(5)} = 0.942$ $\sigma_{e_{(5)}} = 23.35$

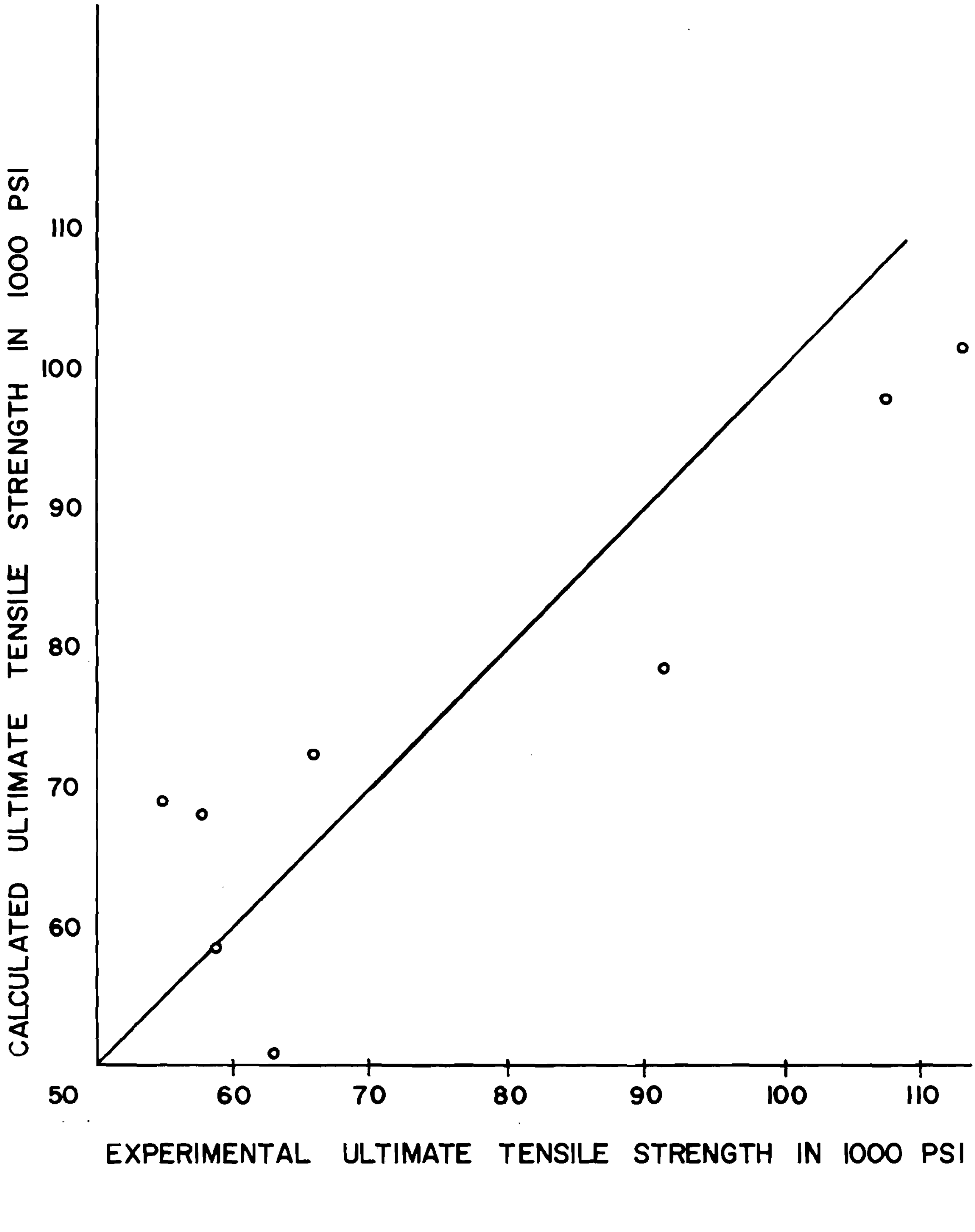

FIGURE 1 EXPERIMENTAL ULTIMATE TENSILE STRENGTH VERSUS CALCULATED ULTIMATE TENSILE STRENGTH FOR SERIES IA-MICROSTRUCTURAL DATA

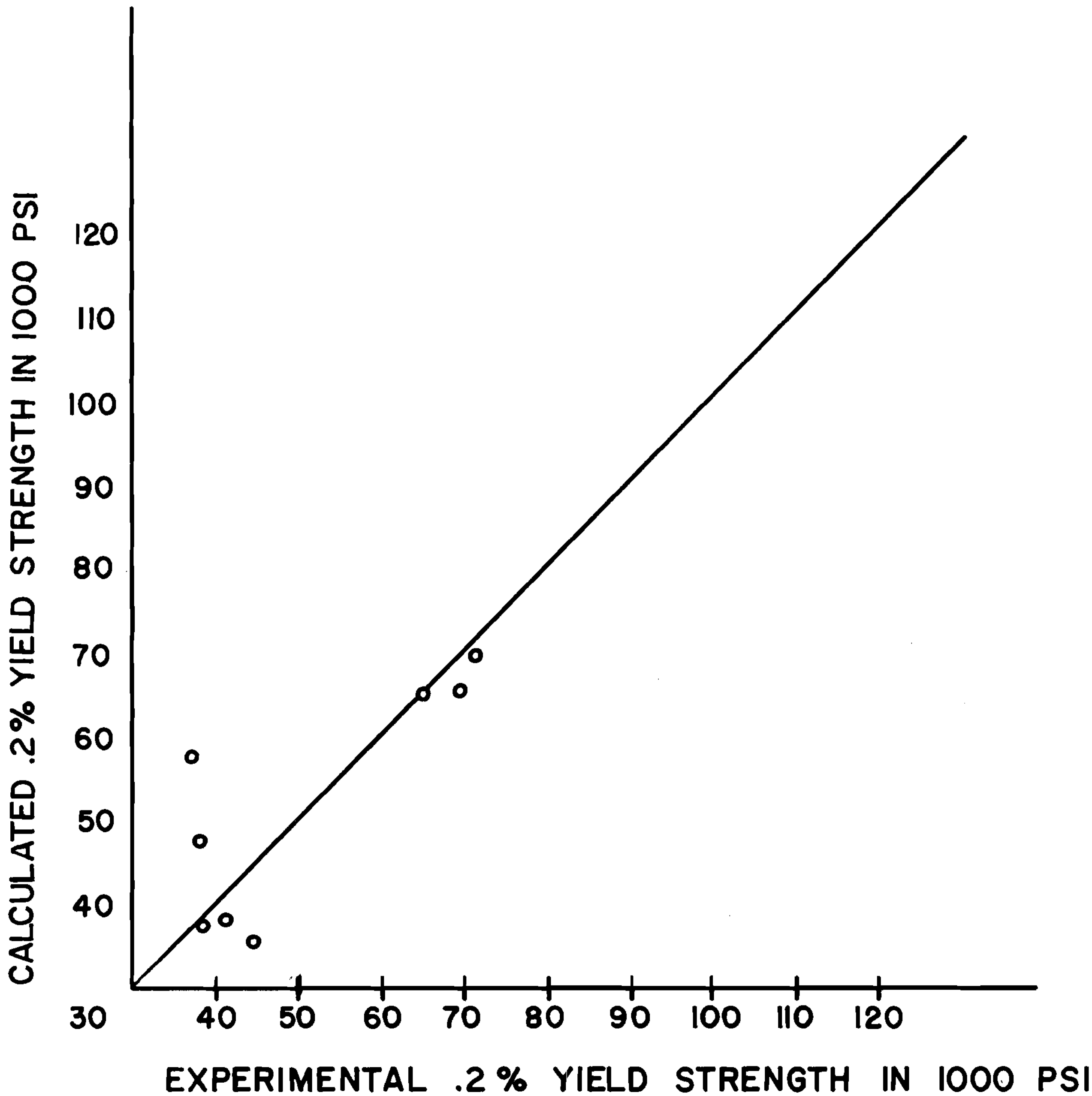

FIGURE 2 EXPERIMENTAL .2 % YIELD STRENGTH VERSUS CALCULATED .2 % YIELD STRENGTH FOR SERIES IA- MICROSTRUCTURAL DATA

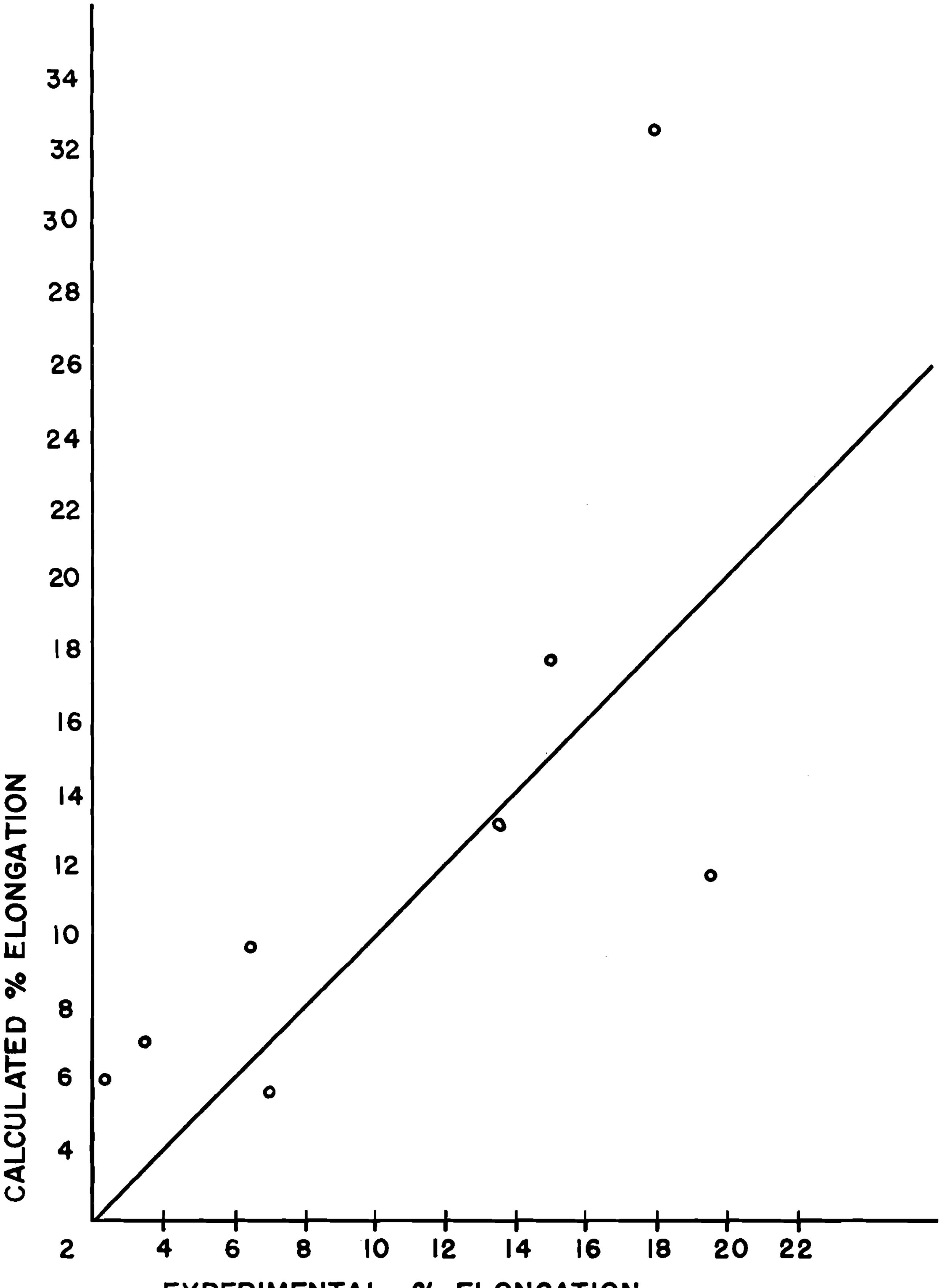

FIGURE 3 EXPERIMENTAL % ELONGATION VERSUS CALCULATED % ELONGATION FOR SERIES IA-MICROSTRUCTURAL DATA

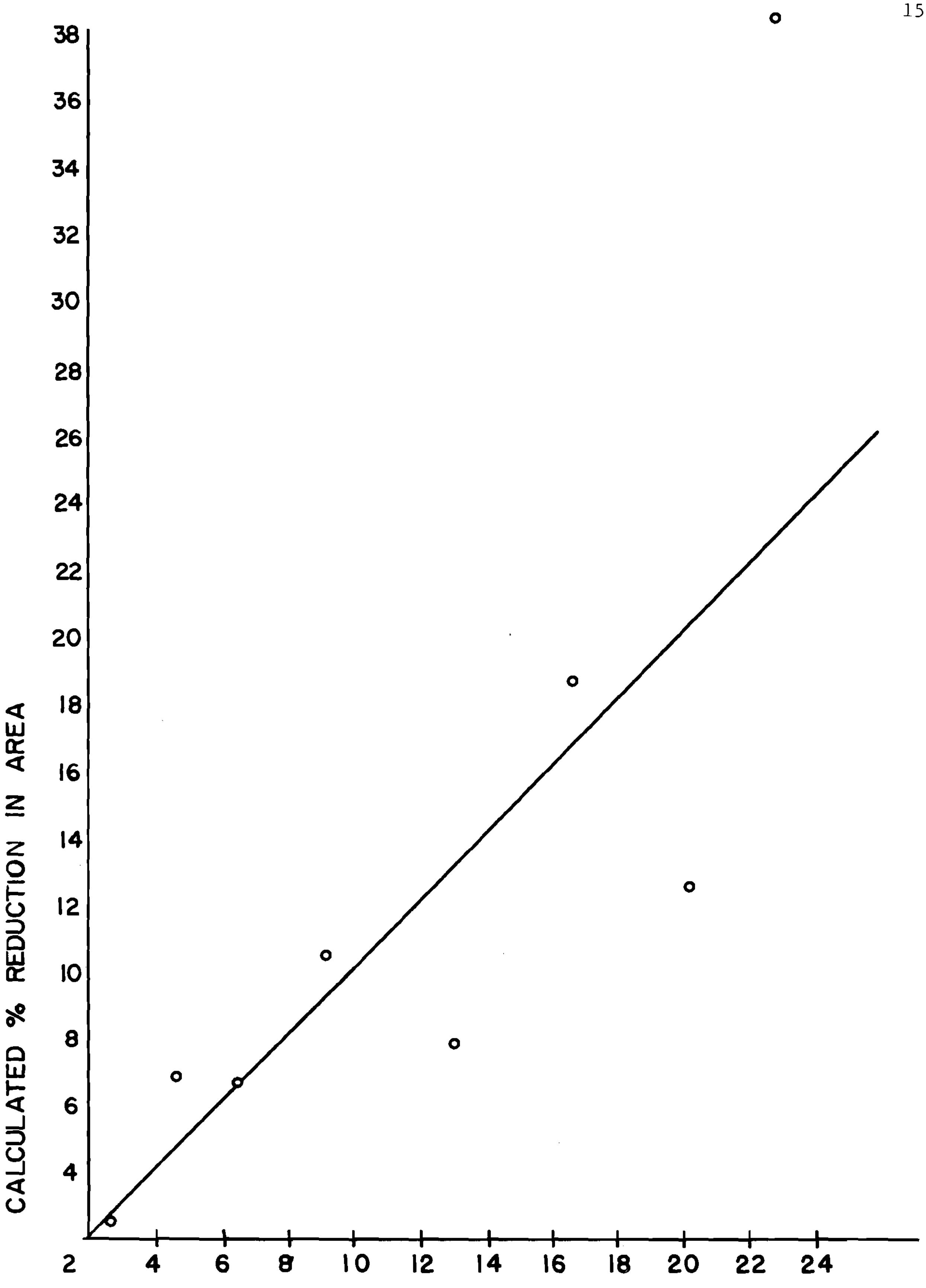

FIGURE 4 EXPERIMENTAL % REDUCTION IN AREA VERSUS CALCULATED % REDUCTION IN AREA FOR SERIES IA-MICROSTRUCTURAL DATA

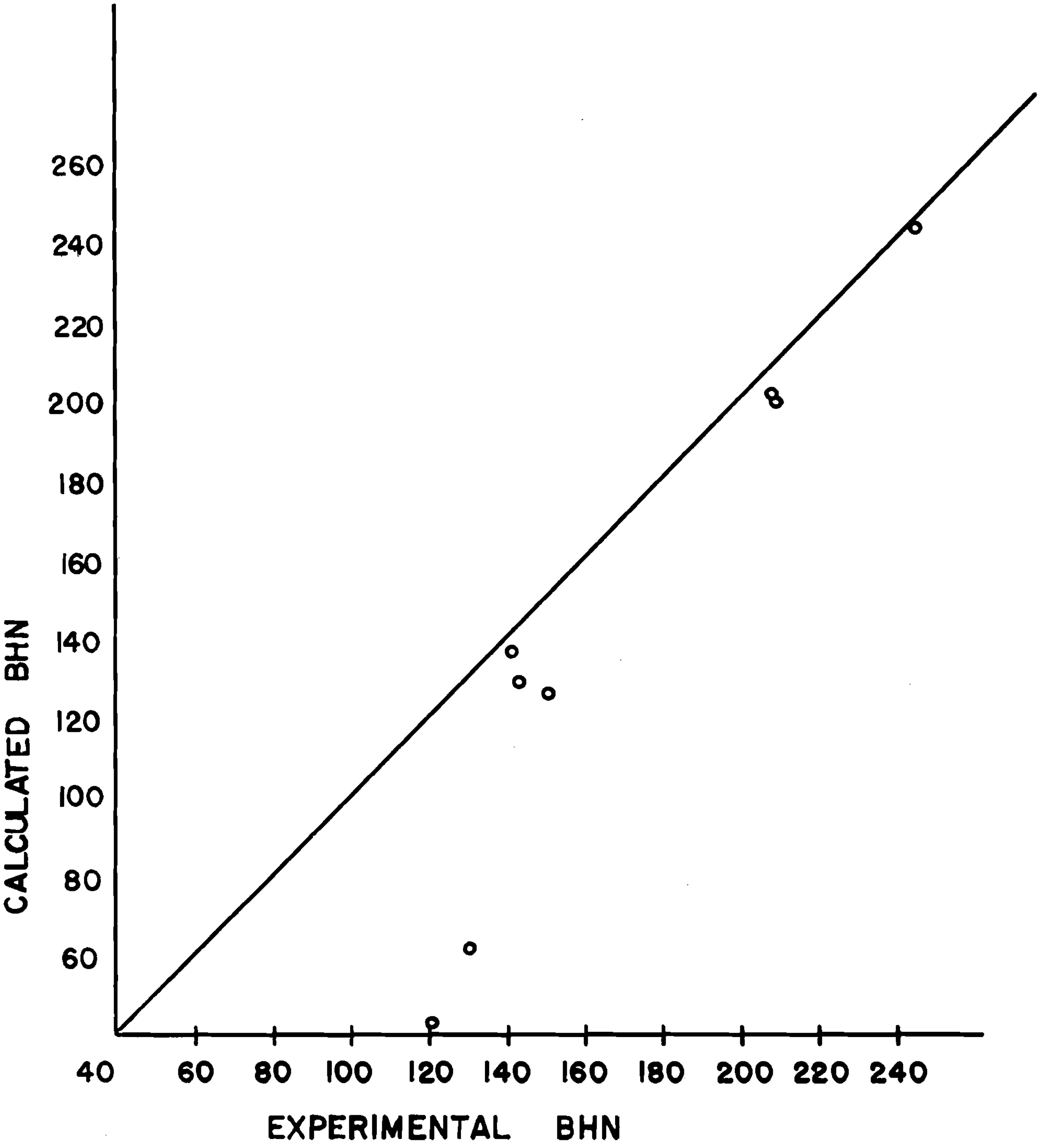

FIGURE 5 EXPERIMENTAL BRINELL HARDNESS VERSUS CALCULATED BRINELL HARDNESS FOR SERIES IA - MICROSTRUCTURAL DATA

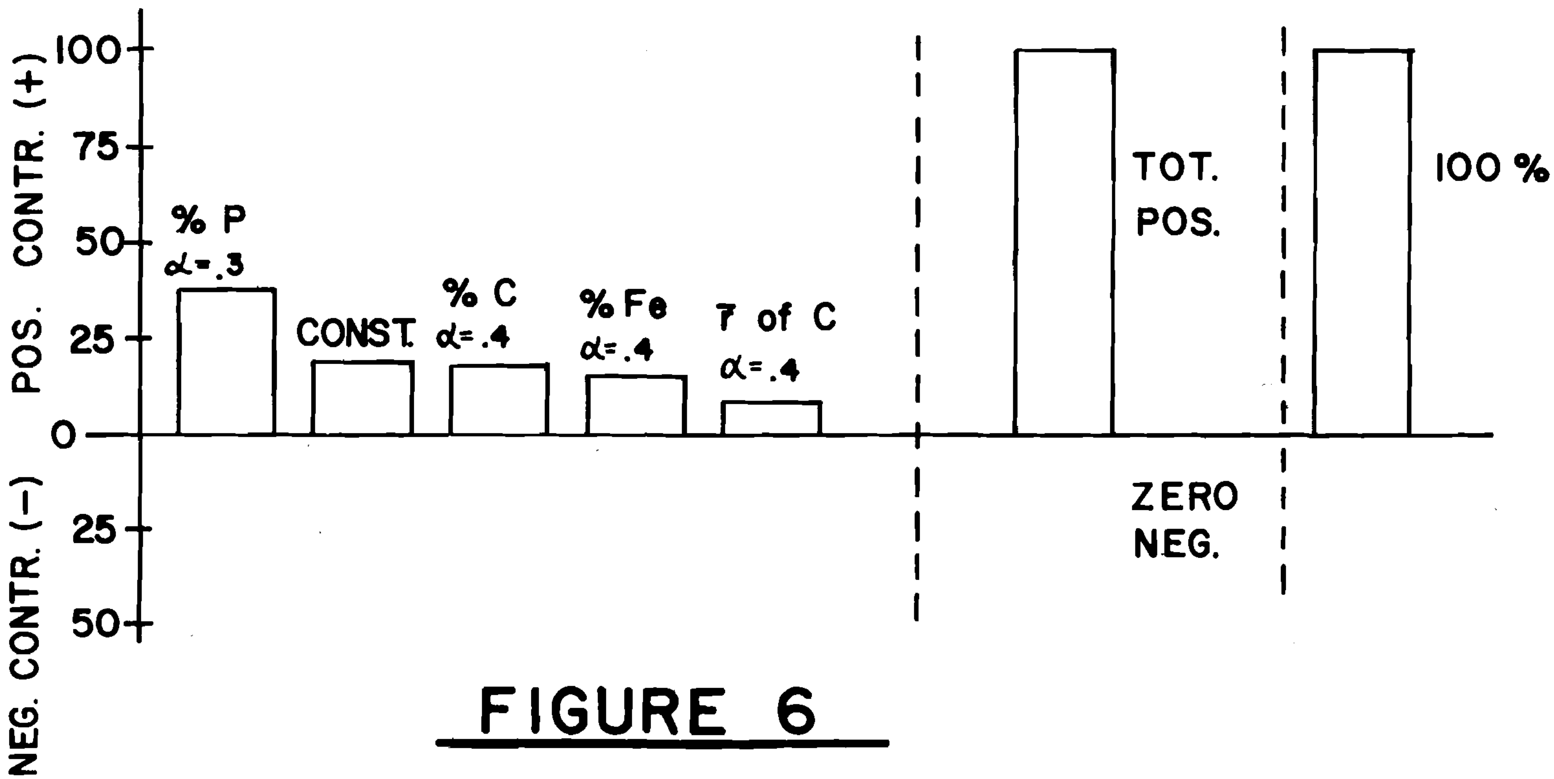

FIGURE 6

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE ULTIMATE TENSILE STRENGTH OF THE SERIES I-A MICROSTRUCTURAL DATA

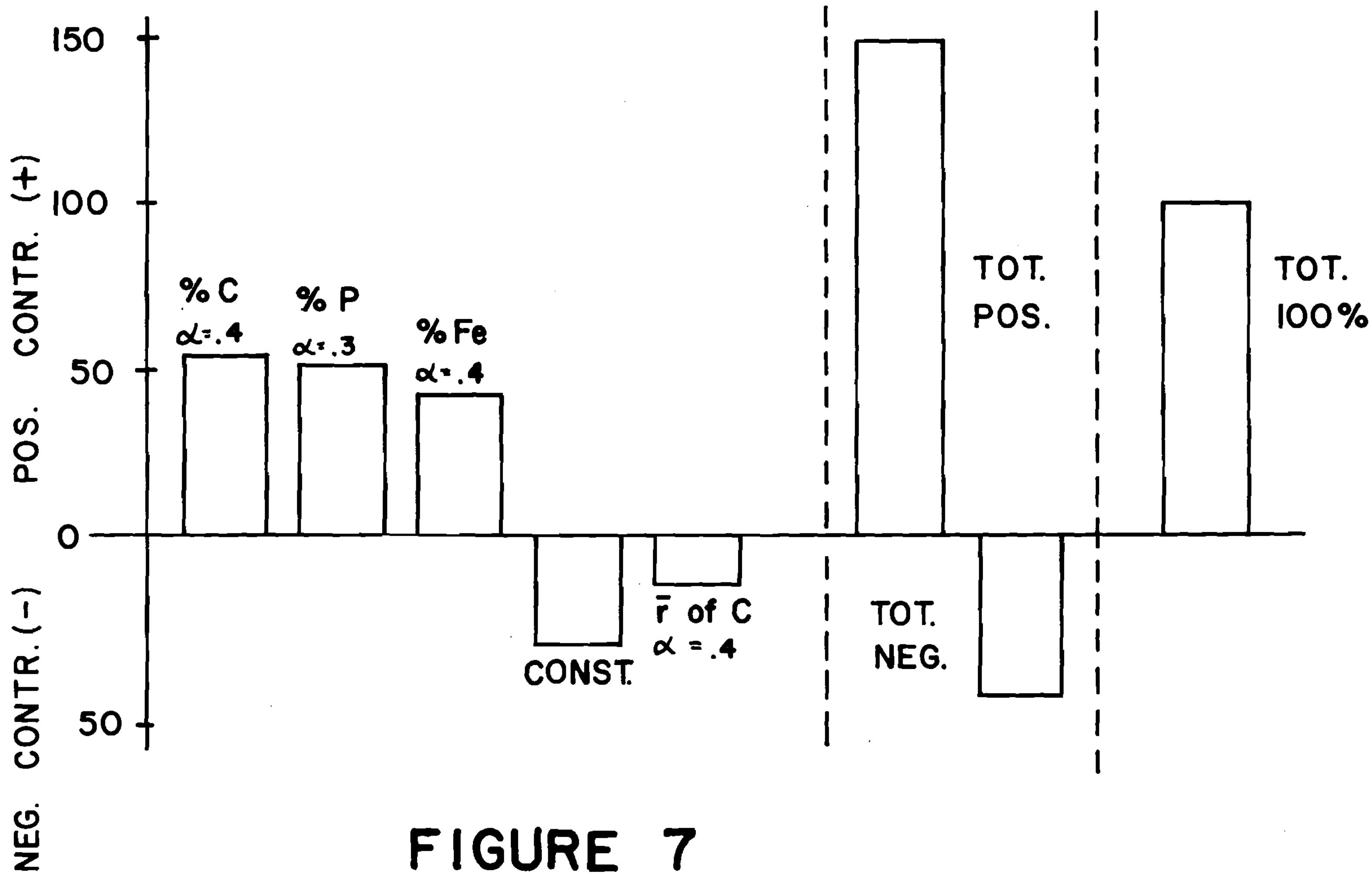

FIGURE 7

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE

0.2 % YIELD STRENGTH

OF THE SERIES I-A MICROSTRUCTURAL DATA

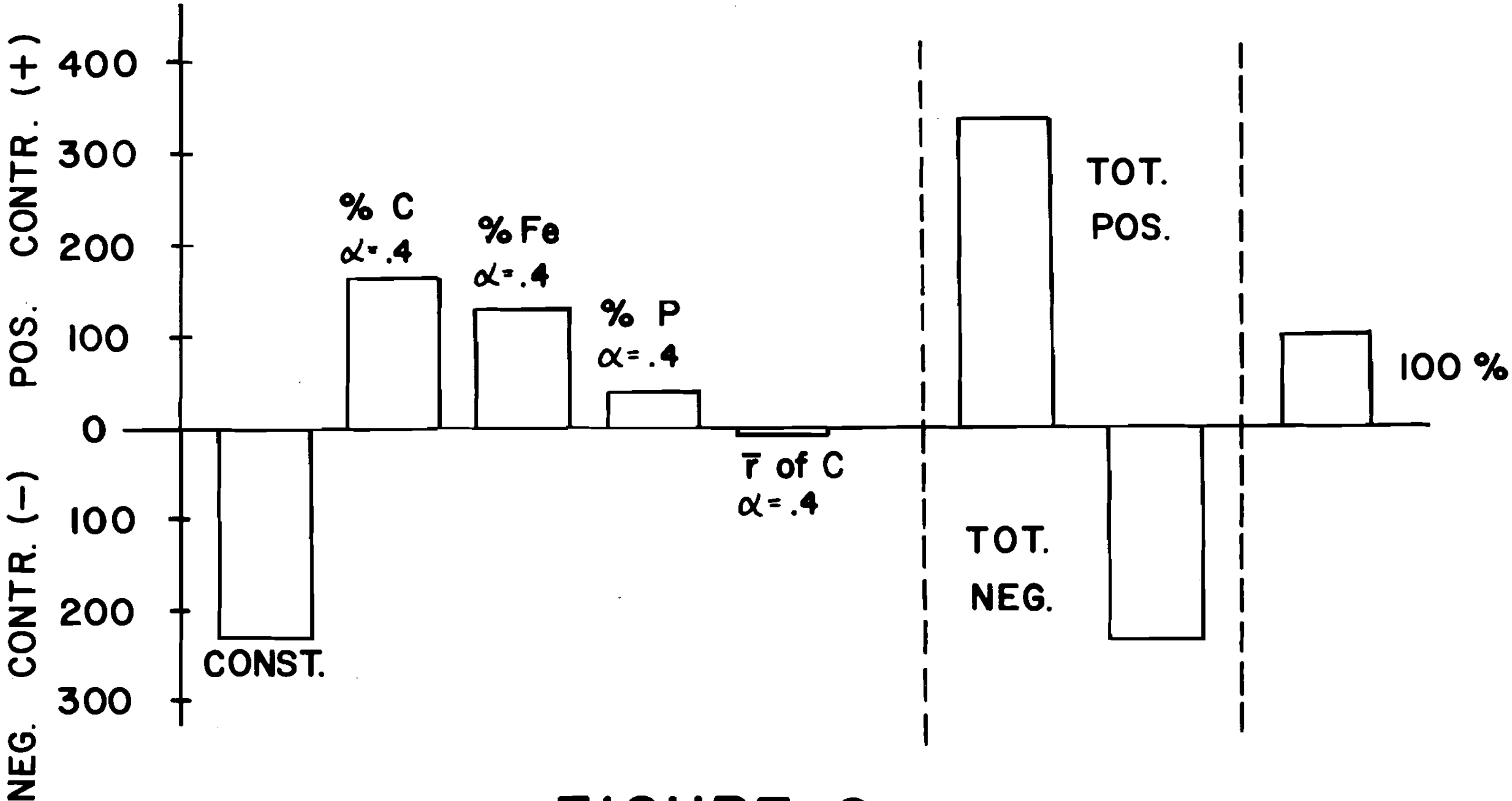

FIGURE 8

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE PERCENT ELONGATION OF THE SERIES I-A MICROSTRUCTURAL DATA

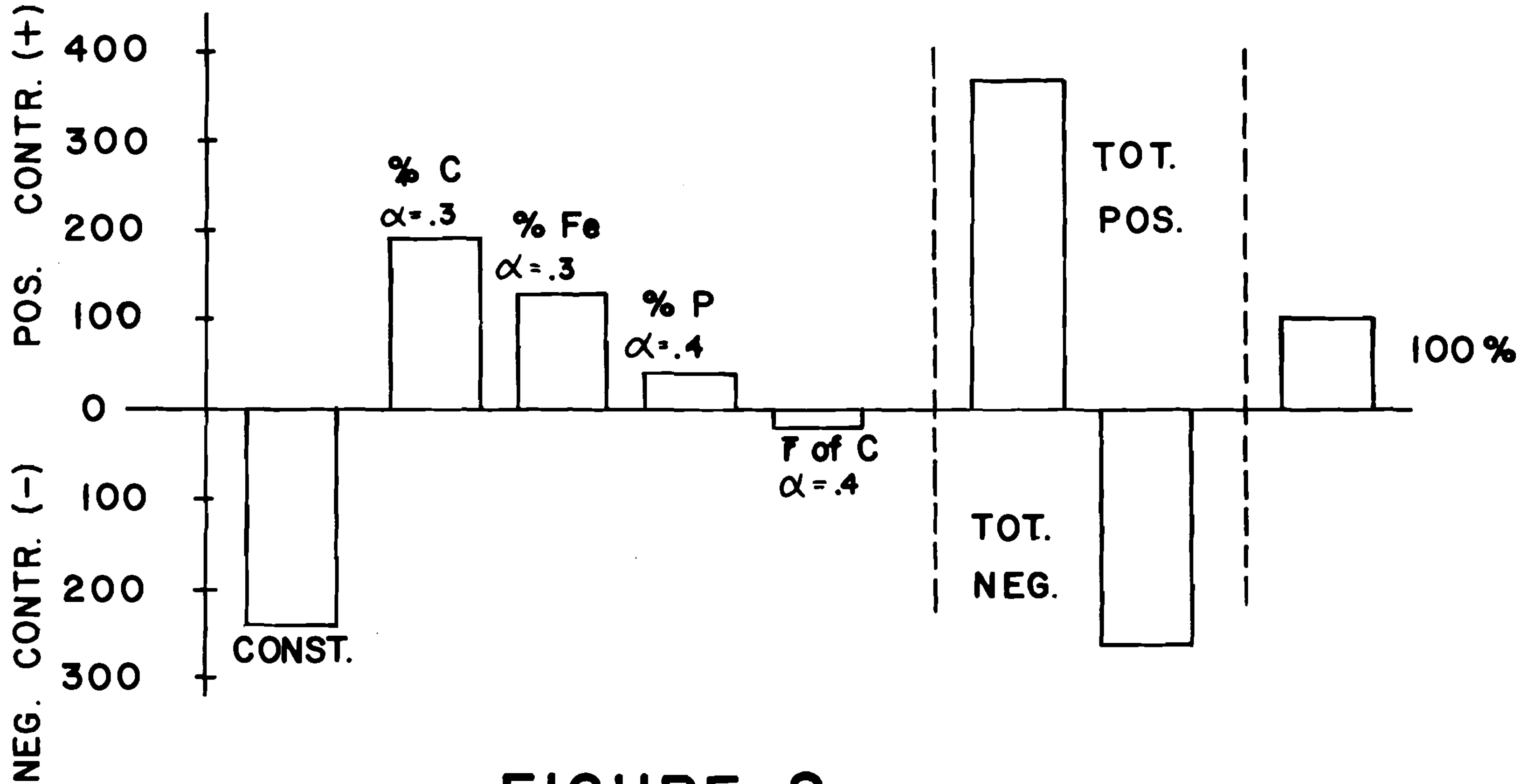

FIGURE 9

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE REDUCTION IN AREA OF THE SERIES I-A MICROSTRUCTURAL DATA

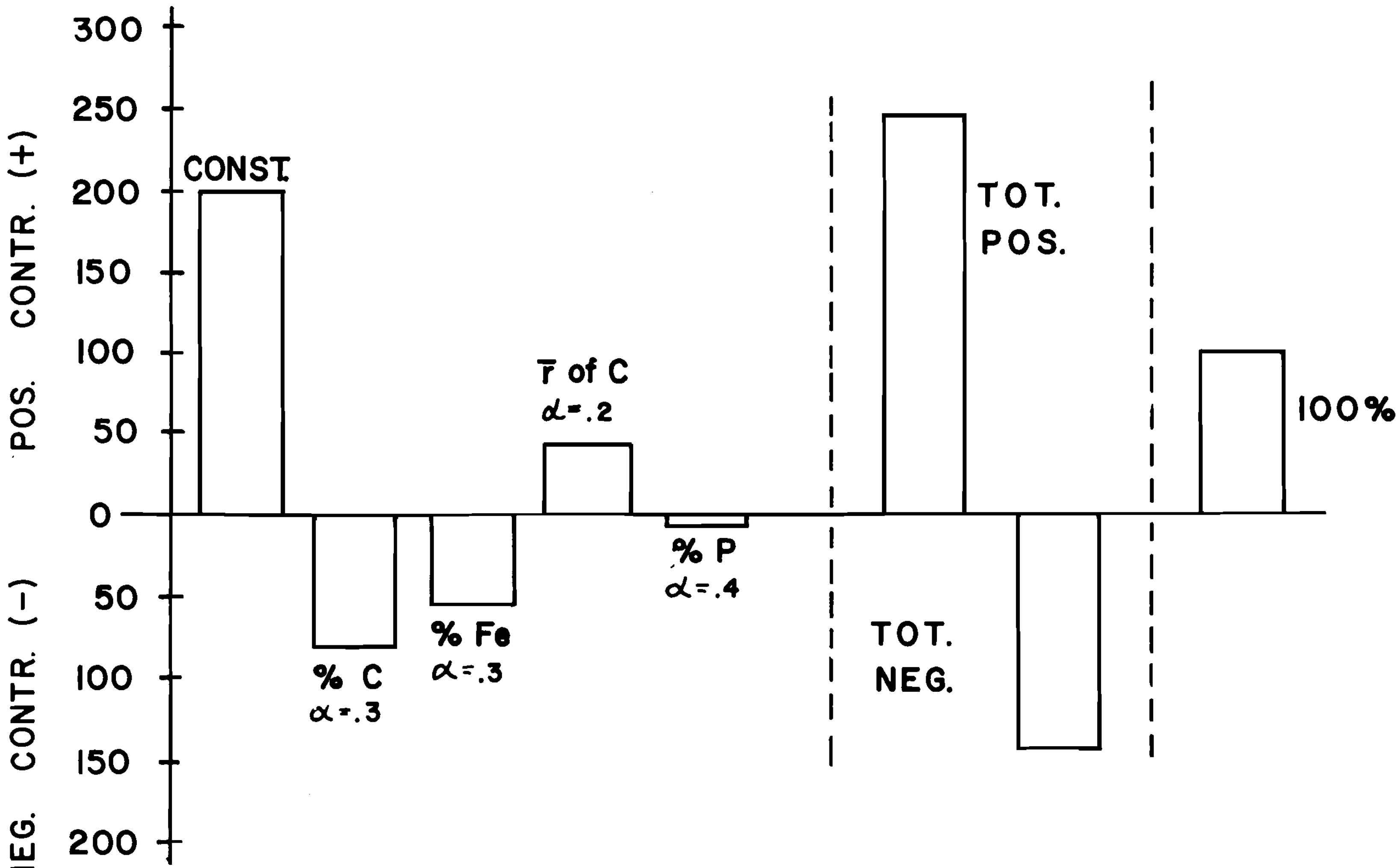

FIGURE 10

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE BRINELL HARDNESS OF THE SERIES I-A MICROSTRUCTURAL DATA

TABLE 5 QUANTITATIVE RESULTS OF THE TENSILE STRENGTH, YIELD STRENGTH, REDUCTION IN AREA, PERCENT ELONGATION AND BRINELL HARDNESS EQUATIONS

Series 1A

		TENSILE STRENGTH		YIELD STRENGTH		PERCENT ELONG.		REDN. IN AREA		BRINELL HARDNESS	
INDEPENDENT VARIABLE	MEAN VALUE	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN. CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERC. CONTR.
VOL. % C	13.6	+14,566	+18.67	+29,213	+54.57	+20.86	+166.88	+27.17	+195.61	-127.84	-80.61
VOL. % P	32.8	+29,750	+38.13	+27,683	+51.71	+4.92	+39.36	+5.51	+39.67	-10.36	-6.53
VOL. % Fe	53.6	+11,953	+15.32	+22,834	+42.66	+16.24	+129.92	+17.80	+128.15	-86.83	-54.75
$\bar{\bar{r}}$ of GRAPHITE	.000964	+6,409	+8.21	-8,299	-15.50	-.679	-5.43	-3.264	-23.50	+66.31	+41.81
CONSTANT		+15,339	+19.66	-17,901	-33.44	-28.84	-230.72	-33.33	-239.96	+317.3	+200.06
MEAN MECH. PROPERTY		+78,017	+100.00	+53,530	+100.00	+12.50	+100.00	+13.89	+100.00	+158.6	+100.00

IV. A. 3. Metallurgical Significance

The sign of the coefficients in each equation gives a qualitative judgment as to the independent variable's contribution towards the magnitude of the dependent variable.

The percentage contribution of each independent variable can also be computed and is simply the ratio of each individual product, and the algebraic sum of all the products, plus the constant. Note at this point that the constant term is given in each of these equations to compensate for the base metal, etc., and any unidentified parameters. However, only the products derived from coefficients whose α's are 0.20 or less should be trusted as somewhat significant.

Thus, from a qualitative point of view, equation 1 indicates that the percent pearlite, percent carbon, percent ferrite and mean radius of the graphite nodules all favor an increase in the tensile strength. Equation 2 shows that while the carbon, pearlite, and ferrite percentages tend to increase the yield strength, the mean nodule radius tends to decrease it. Equations 3 and 4 indicate the contributions of all four independent variables towards the percent elongation and percent reduction in area are the same as in Equation 2. Equation 5 shows that while the mean radius favors a higher BHN, the carbon, ferrite and pearlite percentages favor a lower value.

Figures 6-10 also point out the mean quantitative contribution of each independent variable towards the magnitude of the dependent mechanical properties. These mean quantitative contributions are also listed in Table 5. Further examination of these figures (6-10), however, indicates that none of these values can be trusted in all five equations due to the fact that their individual α's are greater than 0.2.

These Series 1A results are inconclusive due to a minimum number of data sets, but provide a good basis for future analyses.

IV. B. Series 1B Data

The second computer analysis attempted to derive five (5) more mathematical models for each dependent mechanical property as a function of all four (4) independent microstructural variables listed in Table 2. The general form of each of these equations was similar to that given in section IV. A.

IV. B. 1. Linear Regression Models

Equations 6-10 were derived on the basis of twelve (12) sets of data (see Table 2). Solving for the five (5) constants required by the general equation, i.e., A_0, A_1, A_2, A_3 and A_4, leaves seven (7) degrees of freedom for the regression analyses.

The Series 1B models were derived to explain the variation in the ductile cast iron's tensile strength, 0.2% yield strength, percent elongation, percent reduction in area and Brinell hardness number and are listed in Mathematical Model Set II. The correlation coefficient and standard error of estimate are also listed for each of these equations.

IV. B. 2. Statistical Significance

Based upon the computer results, the levels of significance of equations 6, 7, 8, 9 and 10 are 0.025, 0.05, 0.10, 0.05 and 0.05, respectively.

The plotbacks of these five models are illustrated in Figures 11-15 and visually show

MATHEMATICAL MODEL SET II - SERIES 1B

EQUATIONS

TENSILE STRENGTH = + 96,058 - 1,393 (Vol % C) + 334 (Vol % P) - 276 (Vol % Fe) + 3,854,025 ($\bar{r}$)......(6)

$R_{(6)} = 0.907$ $\sigma_{e_{(6)}} = 11,600$

0.2 PERCENT YIELD STRENGTH = + 51,859 - 322 (Vol % C) + 313 (Vol % P) - 63.5 (Vol % Fe) - 3,118,382 ($\bar{r}$).............(7)

$R_{(7)} = 0.854$ $\sigma_{e_{(7)}} = 9,320$

PERCENT ELONGATION = -14,621 + 1.306 (Vol % C) + .086 (Vol % P) + 0.228 (Vol % Fe) - 5,553.7 ($\bar{r}$)........................(8)

$R_{(8)} = 0.760$ $\sigma_{e_{(8)}} = 5.76$

PERCENT REDUCTION IN AREA = -20.0 + 1.83 (Vol % C) + .109 (Vol % P) + .268 (Vol % Fe) - 9,001 ($\bar{r}$)..................(9)

$R_{(9)} = 0.851$ $\sigma_{e_{(9)}} = 5.21$

BRINELL HARDNESS NUMBER (1000 Kg) = + 345.63 - 9.73 (Vol % C) - .543 (Vol % P) - 1.55 (Vol % Fe) + 52,390.0 ($\bar{r}$)................(10)

$R_{(10)} = 0.864$ $\sigma_{e_{(10)}} = 28.3$

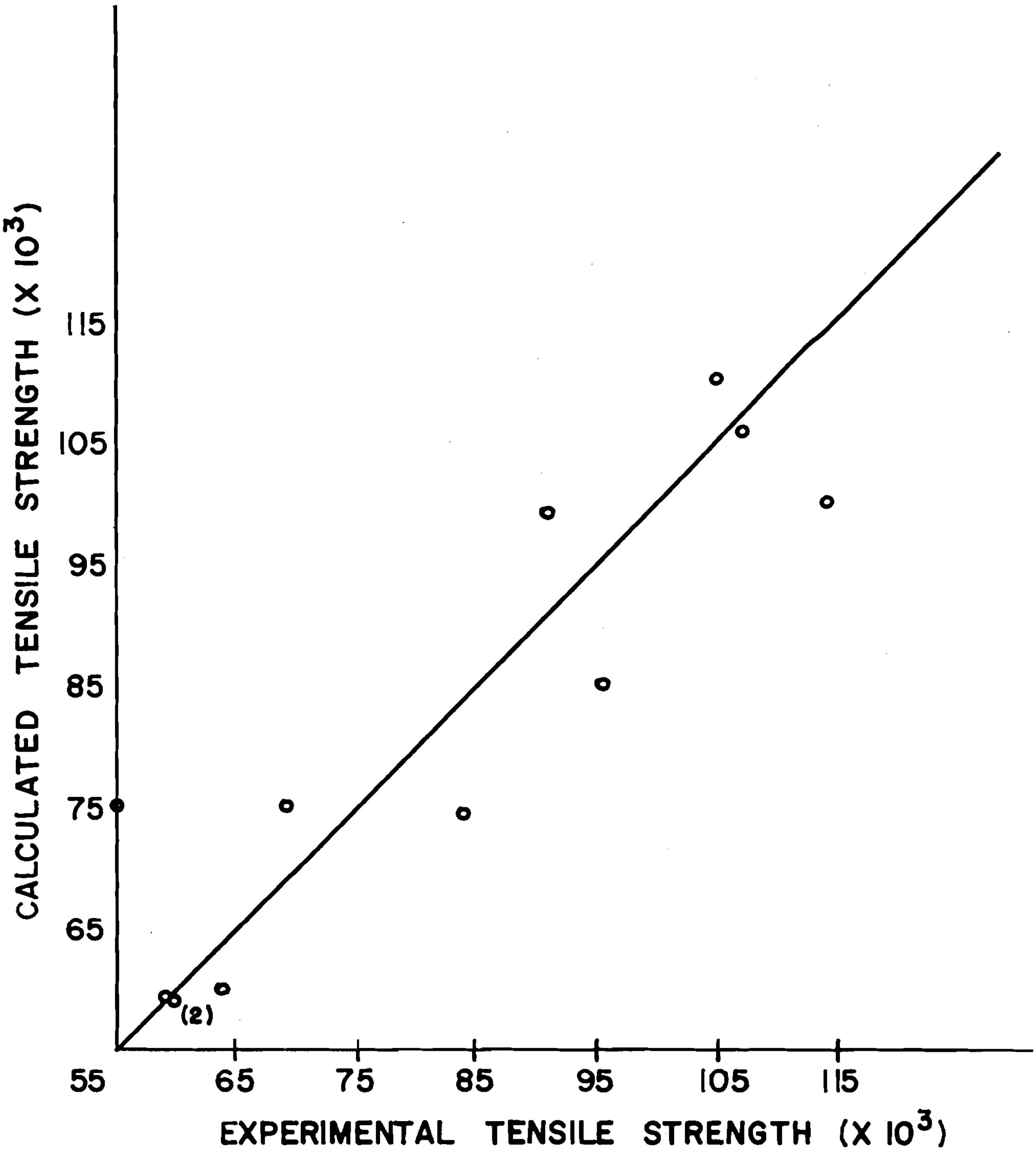

FIGURE 11 EXPERIMENTAL TENSILE STRENGTH VERSUS CALCULATED TENSILE STRENGTH FOR SERIES IB - SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

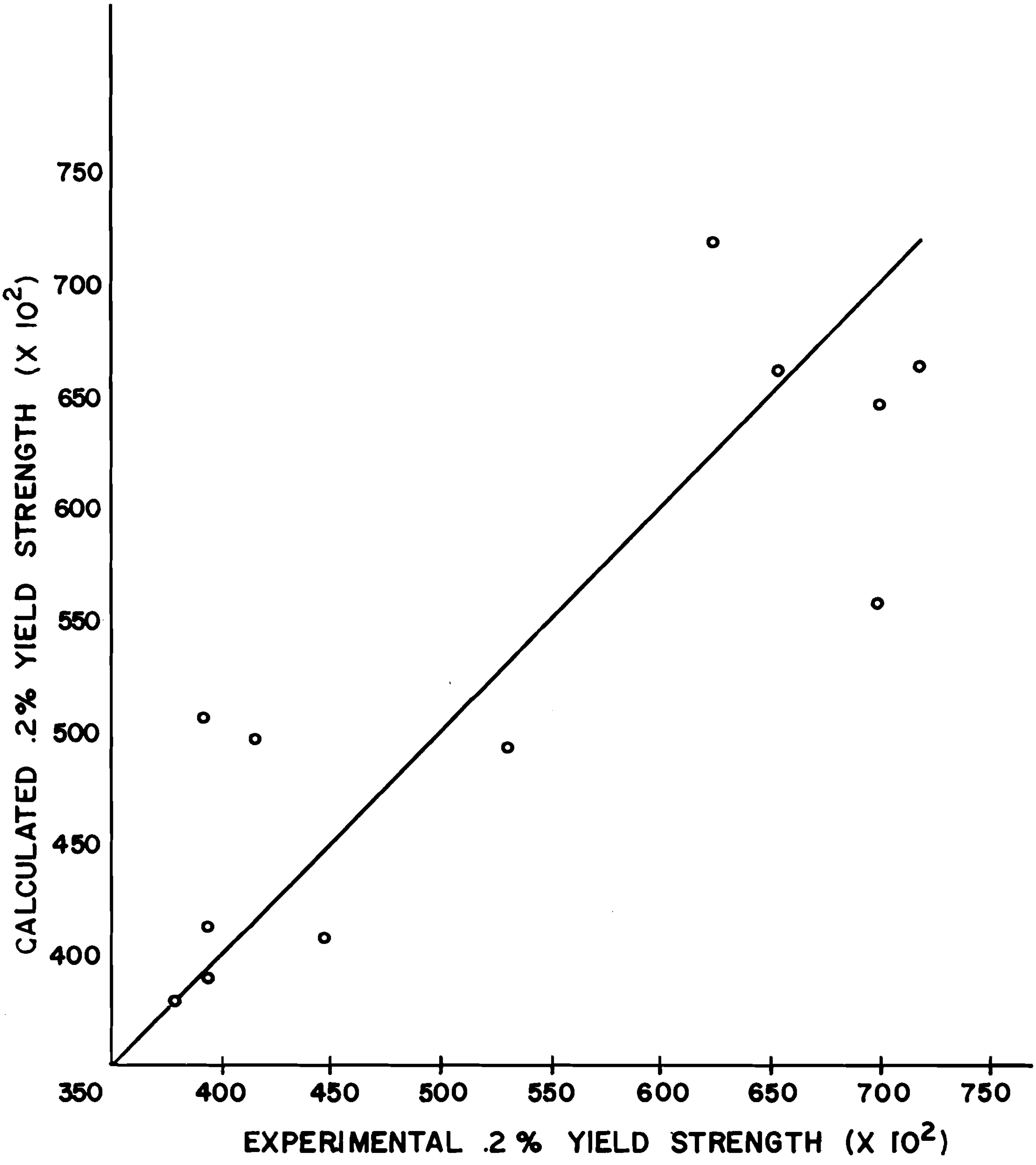

FIGURE 12 EXPERIMENTAL .2 % YIELD STRENGTH VERSUS CALCULATED .2 % YIELD STRENGTH FOR SERIES I B-SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

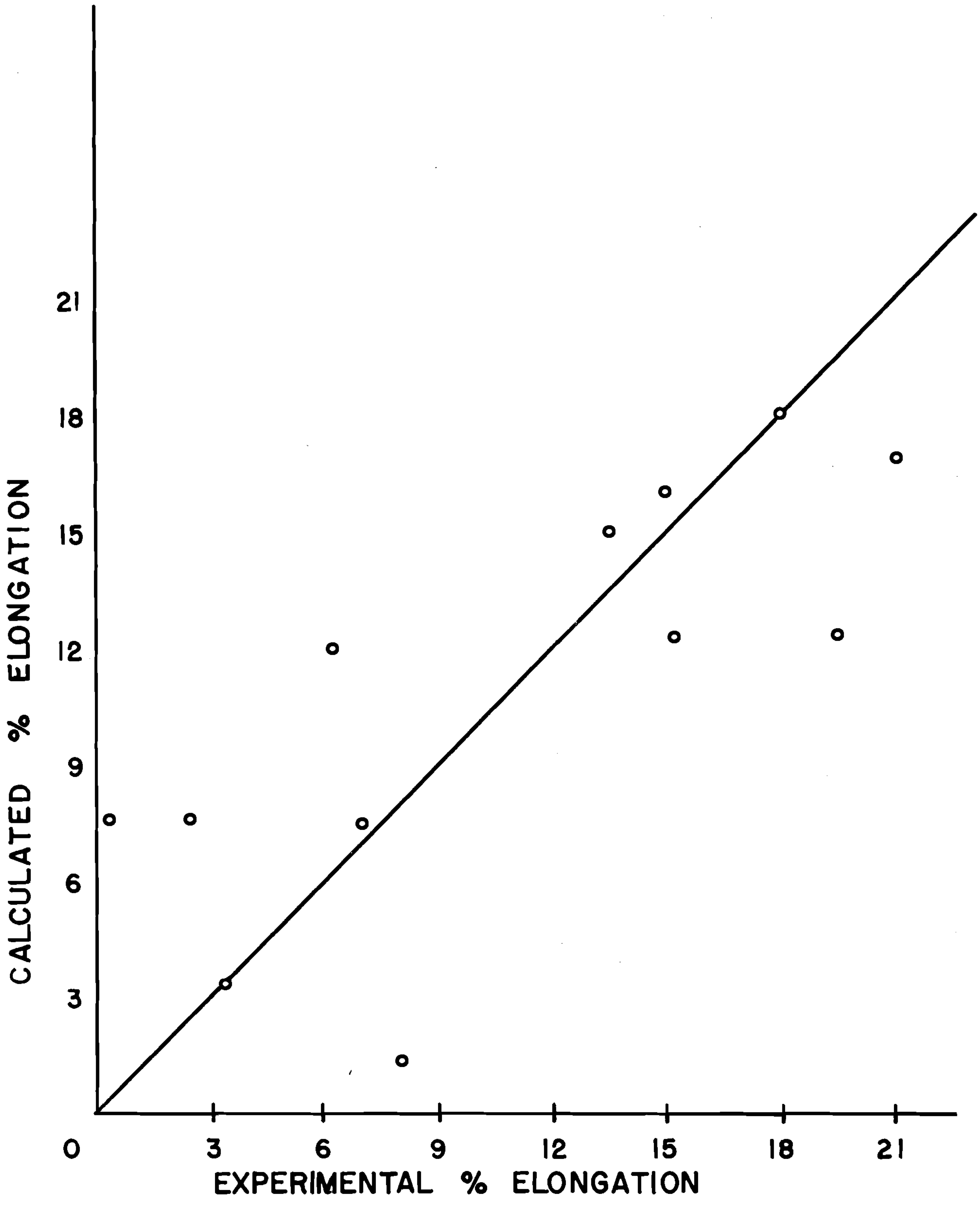

FIGURE 13 EXPERIMENTAL % ELONGATION VERSUS CALCULATED % ELONGATION FOR SERIES IB-SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

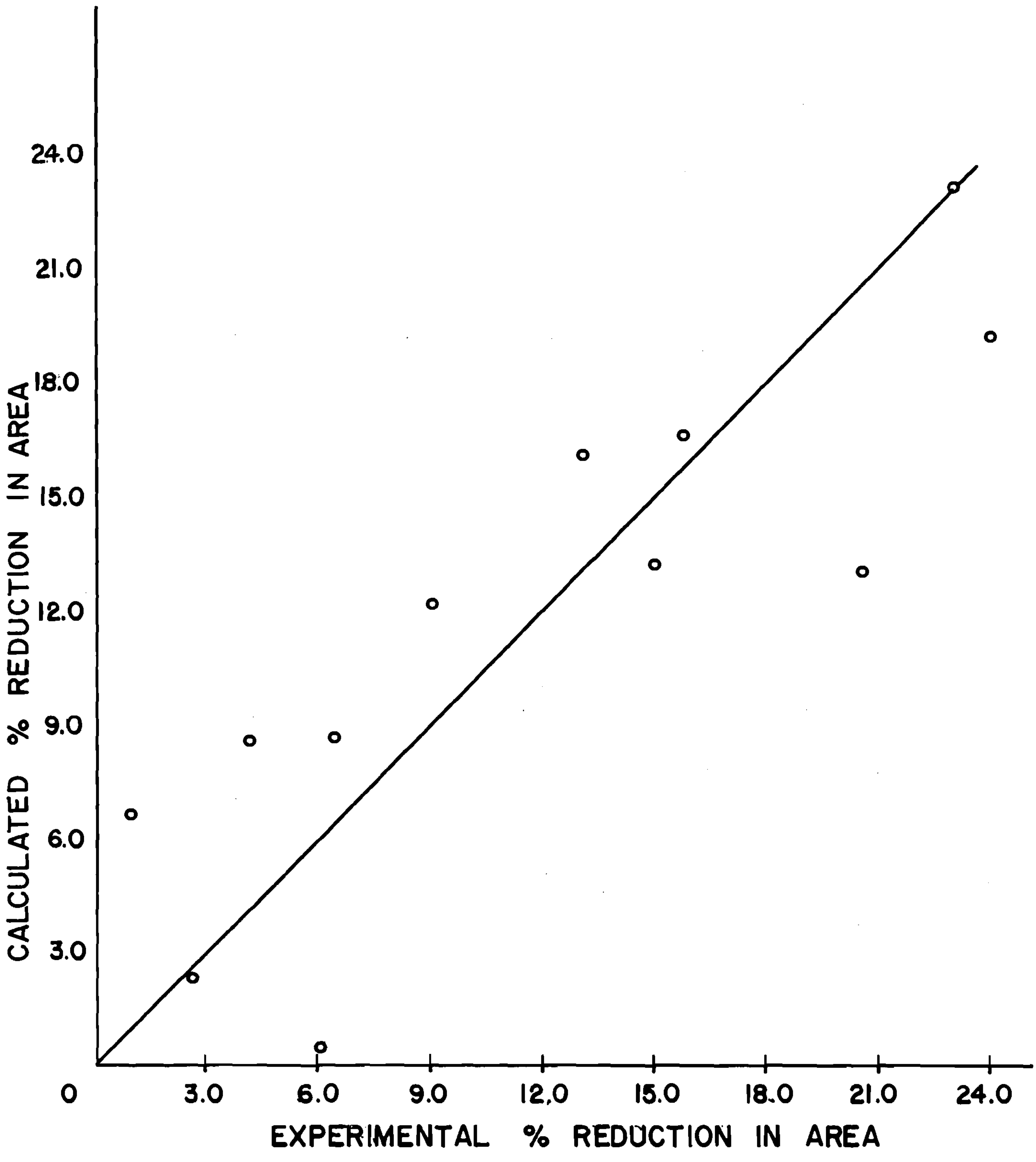

FIGURE 14 EXPERIMENTAL % REDUCTION IN AREA VERSUS CALCULATED % REDUCTION IN AREA FOR SERIES IB - SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

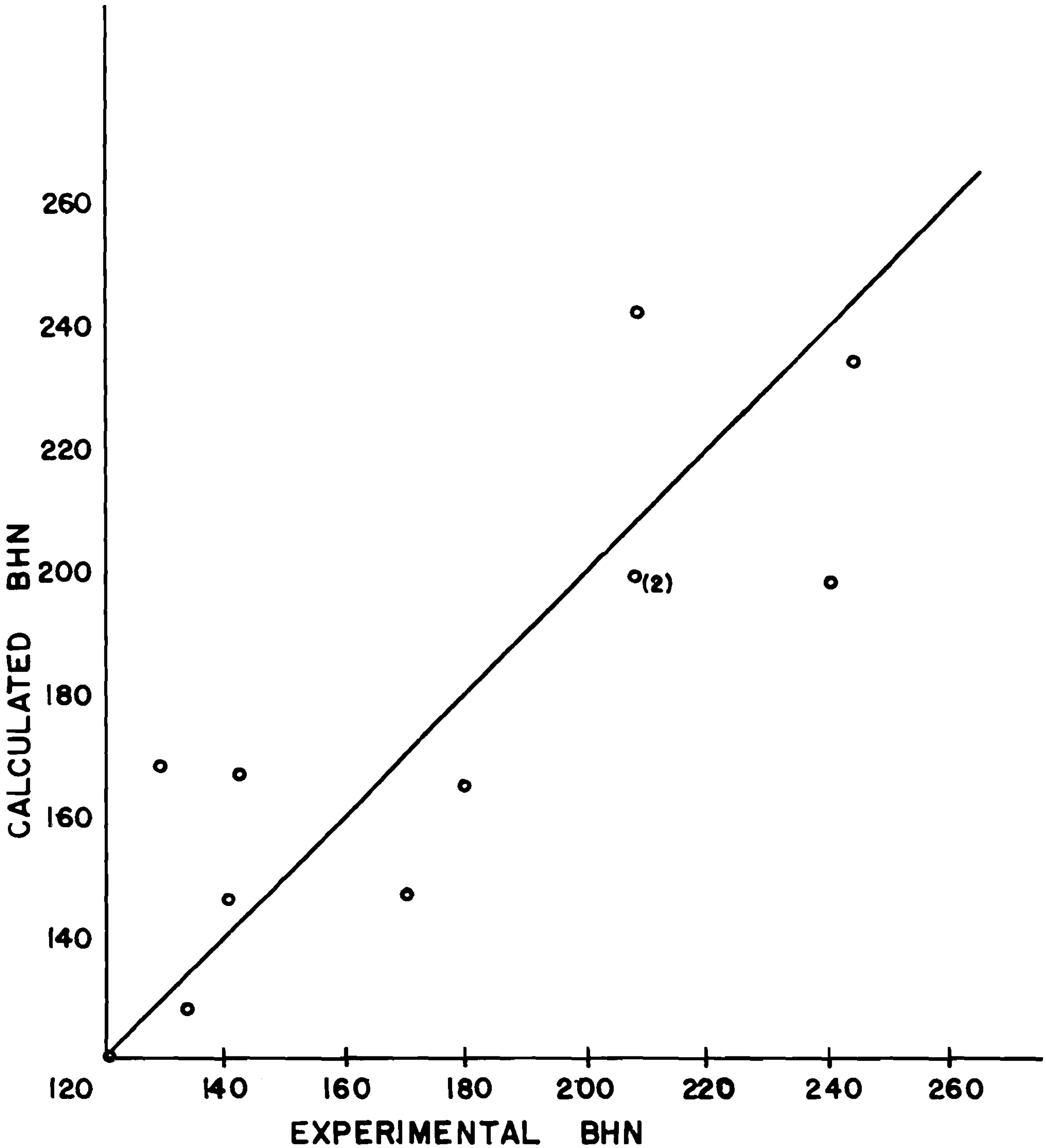

FIGURE 15 EXPERIMENTAL BHN VERSUS CALCULATED BHN FOR SERIES IB- SEQUEL ANALYSIS OF MICRO-STRUCTURAL DATA

the magnitudes of each correlation coefficient.

In addition, Figures 16-20 identify the level of significance of each independent variable contained in equations 6-10. The only individual coefficients statistically significant at the 0.2 confidence level or less appear in equations 9 and 10 (see figures 19 and 20) and include the volume percentages of carbon and ferrite plus the mean radius of the graphite nodules.

IV. B 3. Metallurgical Significance

On a qualitative basis, equation 6 indicates that the volume percent pearlite and mean radius of graphite nodules enhance the tensile strength, while the volume percentages of carbon and ferrite tend to reduce this property. The latter two variables are opposite in their contributions, compared to the results of equation 1, but, model 6 is more acceptable from both a statistical and metallurgical point of view.

Equation 7 shows that the volume percent pearlite increases the yield strength while the other three independent variables tend to decrease this property. The ferrite and pearlite variables are opposite in their contribution, compared to the results of equation 2, but, model 7 is more compatible both statistically and metallurgically.

The qualitative contributions of all four independent variables in equations 8, 9 and 10 towards the magnitudes of the percent elongation, percent reduction in area and Brinell hardness number, respectively, are the same as they were in equations 3, 4 and 5. Equation 9 and 10, however, are more acceptable statistically.

Figures 16-20 also point out the mean quantitative contribution of each independent variable towards the magnitude of the dependent mechanical properties. These mean values for each equation are also listed in Table 6. Further examination of figures 16-20 shows that the only values of the independent variables that should be experimented with for improved mechanical property attainment should be the carbon, ferrite and mean radius parameters contained in equations 9 and 10, due to the fact that their individual α's are 0.2, or less.

These Series 1B results are more conclusive than those achieved in Series 1A, but additional data sets are required for an in-depth analysis.

IV. C. Series 2A Data

The third computer analysis attempted to derive four (4) mathematical models for each dependent, as cast, mechanical property as a function of all six (6) independent elemental variables listed in Table 3. The general form of each of these equations was as follows:

$$\begin{aligned} \text{MECHANICAL PROPERTY} = {} & B_0 + B_1 \text{ (Total Percent Carbon)} + B_2 \text{ (Percent Silicon)} \\ & + B_3 \text{ (Percent Manganese)} + B_4 \text{ (Percent Nickel)} \\ & + B_5 \text{ (Percent Molybdenum)} + B_6 \text{ (Percent Magmesium)} \end{aligned}$$

IV. C. 1 Linear Regression Models

All four (4) equations were derived from as cast properties and were based on fifteen (15) sets of data (see Table 3). Solving for the seven (7) constants required by the general equation, i.e., B_0, B_1-B_6, leaves eight (8) degrees of freedom for the regression analyses.

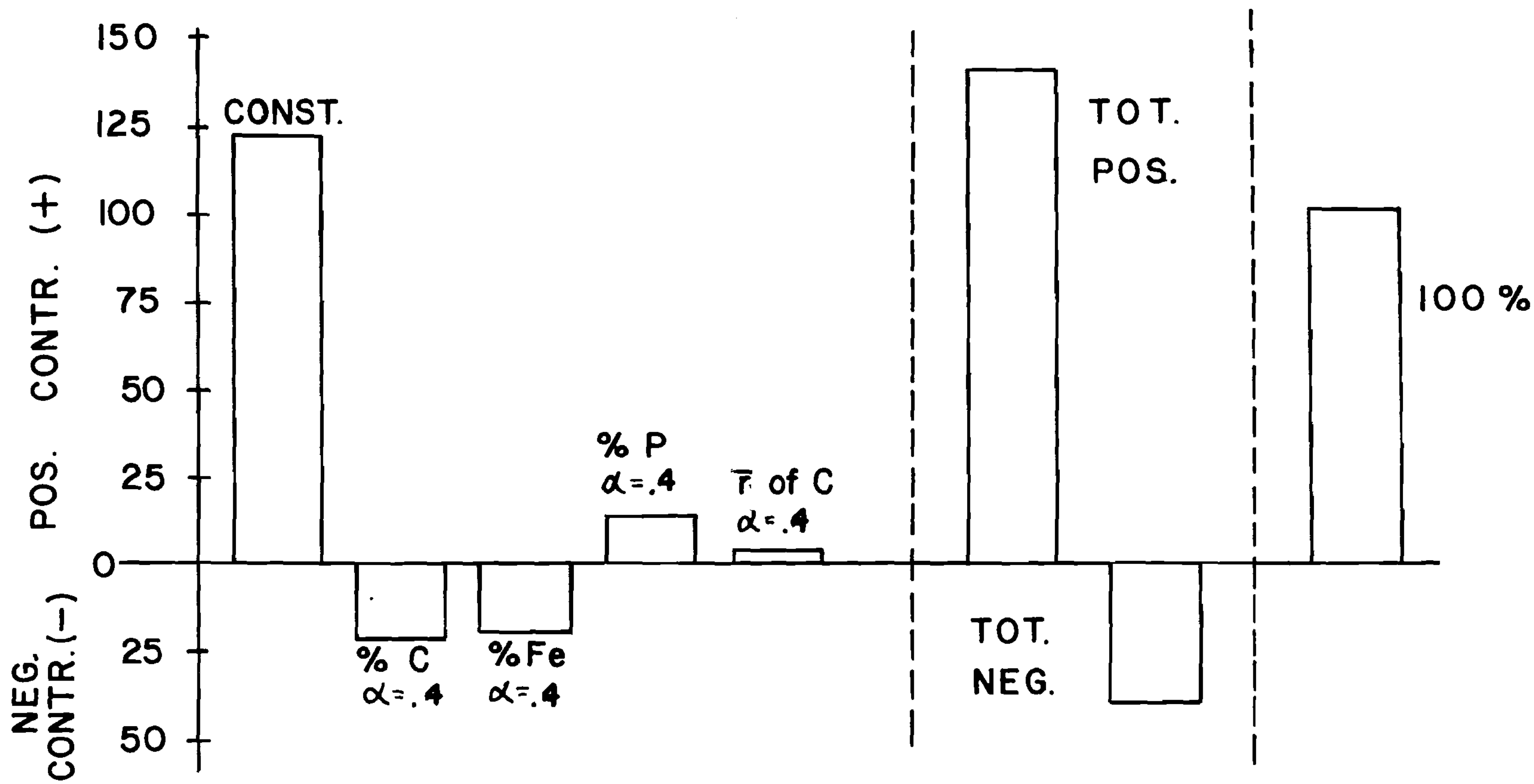

FIGURE 16

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE ULTIMATE TENSILE STRENGTH OF THE SERIES I-B SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

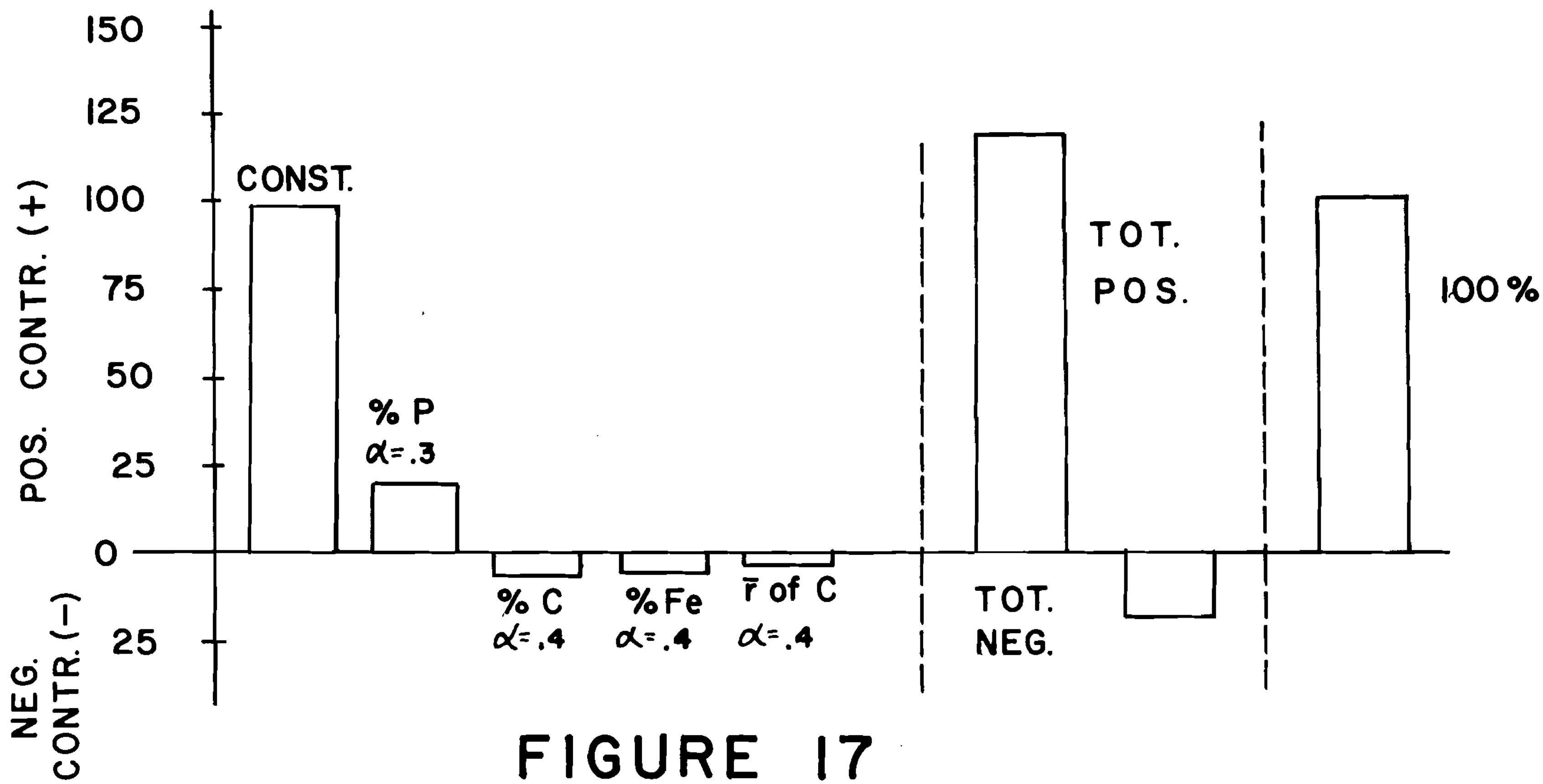

FIGURE 17

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE 0.2 % YIELD STRENGTH OF THE SERIES I-B SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

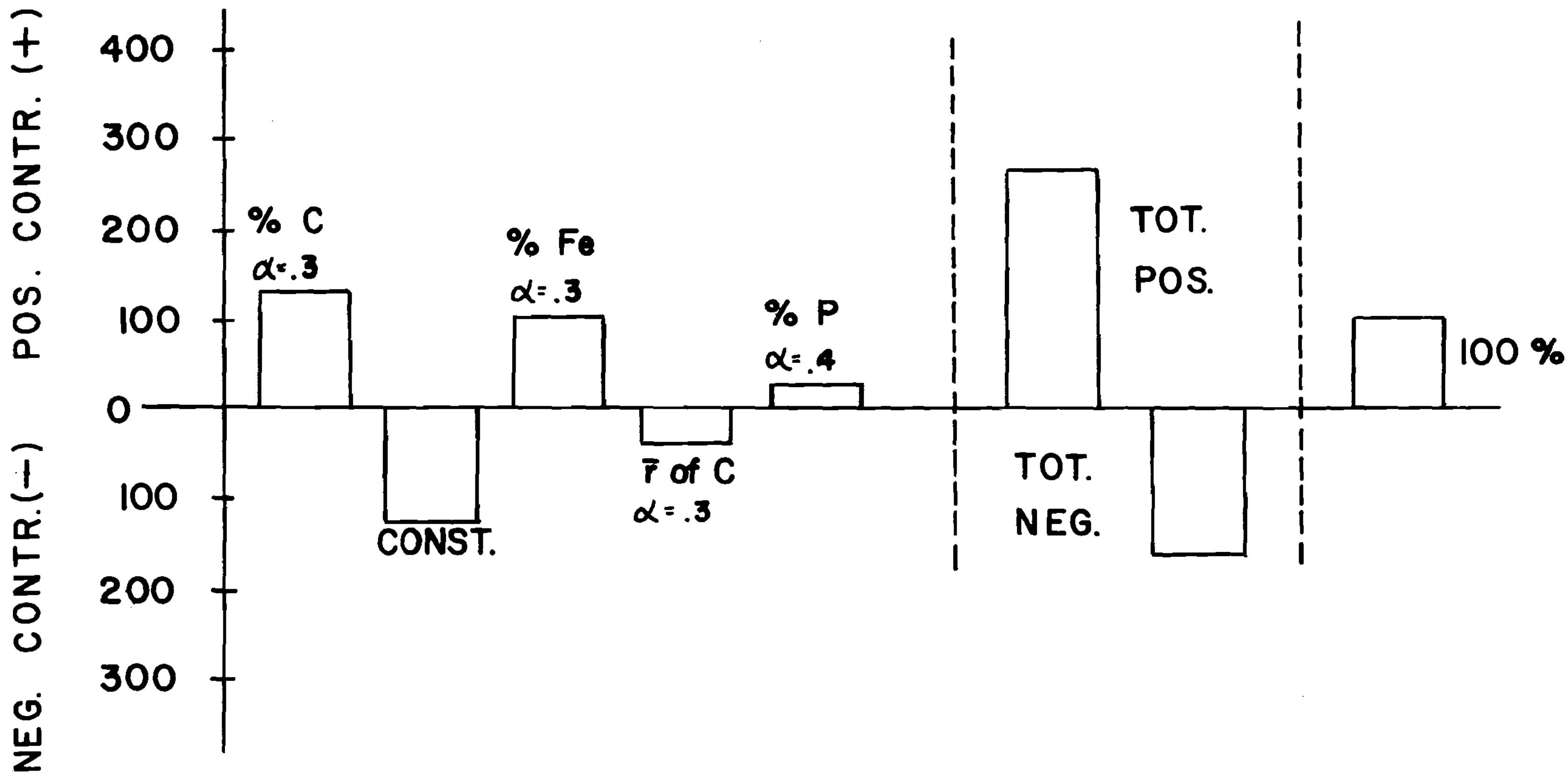

FIGURE 18

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE

PERCENT ELONGATION

OF THE SERIES I-B SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

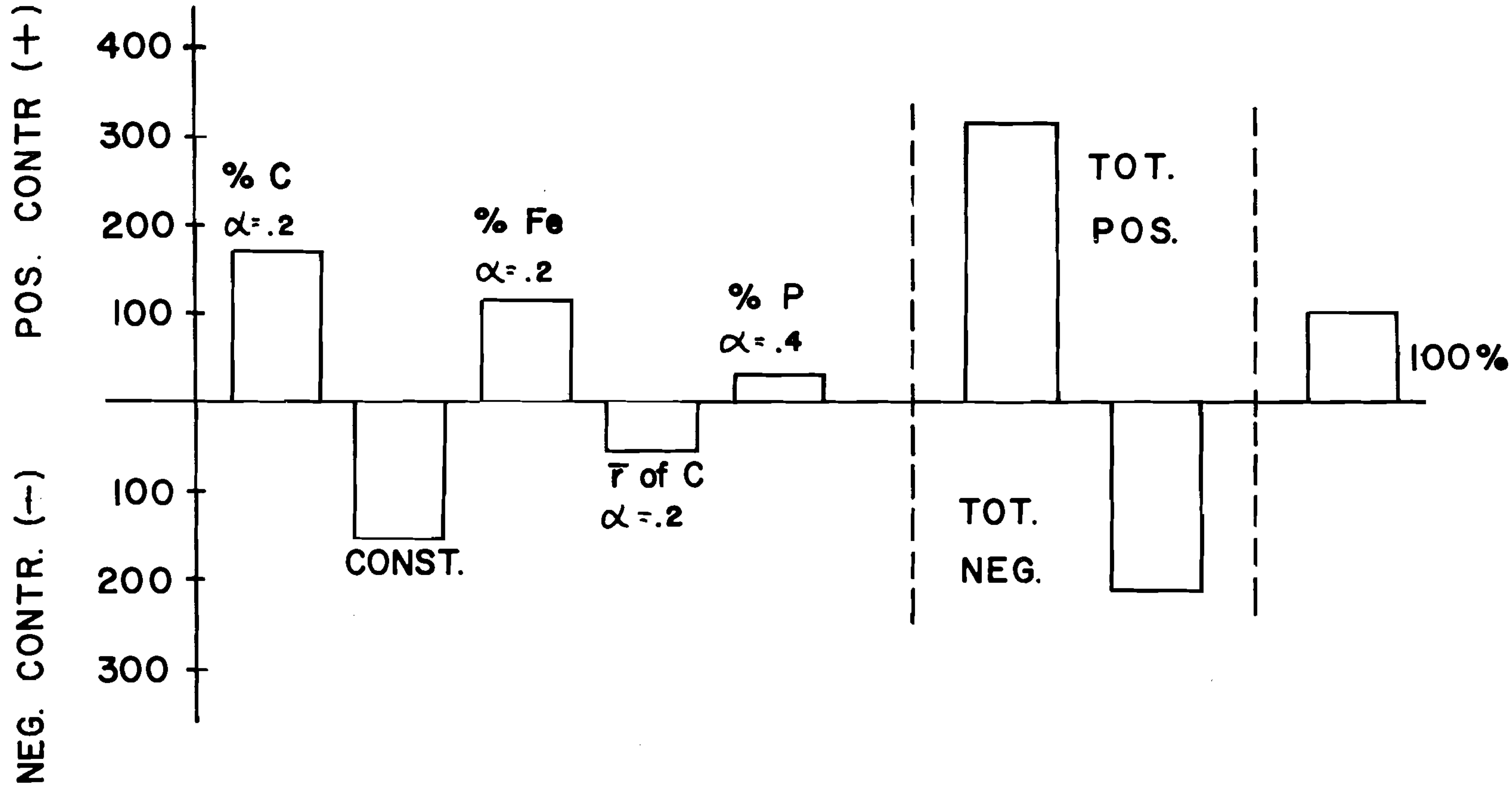

FIGURE 19

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE REDUCTION IN AREA OF THE SERIES I-B SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

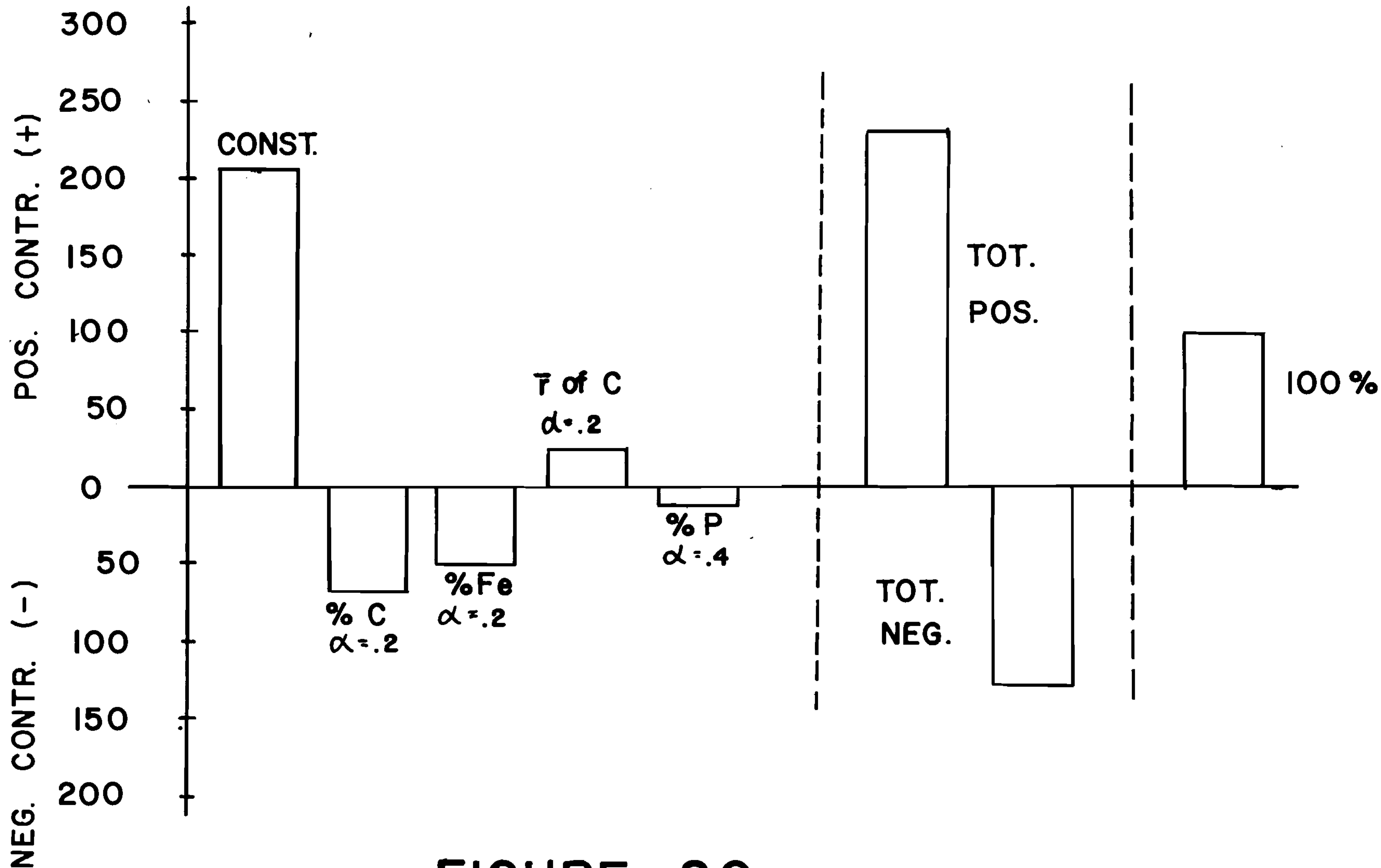

FIGURE 20

PERCENT CONTRIBUTION OF THE INDEPENDENT VARIABLES TO THE

BRINELL HARDNESS

OF THE SERIES I-B SEQUEL ANALYSIS OF MICROSTRUCTURAL DATA

TABLE 6 QUANTITATIVE RESULTS OF THE TENSILE STRENGTH, YIELD STRENGTH, REDUCTION OF AREA, PERCENT ELONGATION, AND BRINELL HARDNESS EQUATIONA

Series 1B

		TENSILE STRENGTH		YIELD STRENGTH		PERCENT ELONG.		REDN. OF AREA		BRINELL HARDNESS	
INDEPENDENT VARIABLE	MEAN VALUE	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.
VOL. % C	12.0	-16,716	-21.27	-3,864	-7.38	+15.67	-133.36	+21.96	+172.37	-116.76	-68.80
VOL. % P	33.3	+11,122	+14.15	+10,423	+19.91	+2.86	+24.34	+3.63	+28.49	-18.08	-10.65
VOL. % Fe	54.7	-15,097	-19.21	-3,473	-6.63	+12.47	+106.13	+14.66	+115.07	-84.79	-49.96
$\bar{r}$ of GRAPHITE	.000834	+3,214	+4.09	-2,601	-4.97	-4.63	-39.40	-7.51	-58.95	+43.69	+25.75
CONSTANT		+96,058	+122.24	+51,859	+99.07	-14.62	-124.43	-20.0	-156.99	+345.6	+203.65
MEAN MECH. PROPERTY		+78,581	+100.00	+52,344	+100.00	+11.75	+100.00	+12.74	+100.00	+169.7	+100.00

These Series 2A models were derived to explain the variation in the ductile cast iron's as cast, tensile strength, 0.2% yield strength, percent elongation and Brinell hardness number and are listed in mathematical Model Set III.

IV. C. 2. Statistical Significance

The computer results indicate that the levels of significance of equations 11, 12, 13 and 14 are 0.1, 0.1, 0.1 and 0.05, respectively.

The plotbacks of these four models are illustrated in Figures 21-24 and visibly show the poor values of each correlation coefficient.

Also, Figures 25-28 identify the level of significance of each independent variable contained in equations 11-14. The only individual coefficients statistically significant at the 0.2 confidence level or less appear in equations 11 and 14, i.e., the tensile strength and Brinell hardness number models. The carbon, silicon and manganese coefficients were the significant ones in model II while the manganese, nickel, molybdenum and magnesium coefficients fell in this category in model 14.

IV. C. 3. Metallurgical Significance

From a qualitative point of view, equation 11 shows that while carbon and magnesium enhance the as cast tensile strength, silicon, manganese, nickel and molybdenum tend to reduce this property. Equation 12 indicates that silicon, manganese, molybdenum and manganese tends to increase the yield strength while carbon and nickel reduce it. Equation 13 shows that manganese, molybdenum and magnesium enhance the percent elongation while carbon, silicon and nickel lower it. Finally, equation 14 indicates that carbon, manganese, nickel and molybdenum contribute positively towards the Brinell hardness number while silicon and manganese are negative contributors.

Figures 25-28 and Table 7 illustrate the mean quantitative contribution of each independent elemental variable towards the magnitude of the dependent mechanical properties. Further examination of these four latter figures, however, shows that only the tensile strength and Brinell equations contain independent variables significant at the 0.2 confidence level or less.

These Series 2A results are inconclusive due to the high confidence levels of the equations and independent variables. Several reasons for these poor statistical outputs could be attributed to lack of sufficient data sets and the as cast conditions of this series of test bars.

IV. D. Series 2B Data

The fourth computer analysis attempted to derive four (4) more mathematical models for each normalized, ductile cast iron's mechanical property as a function of all six (6) independent, elemental variables listed in Table 4. The general form of each of these equations was similar to that given in Section IV. C.

IV. D. 1. Linear Regression Models

Equations 15-18 were derived on the basis of thirteen (13) sets of data (see Table 4). Solving for the seven (7) constants required by the general equation, i.e., B_0, B_1-B_6, leaves only six (6) degrees of freedom for the regression analyses.

These Series 2B models were generated to describe the variation in the normalized, ductile cast iron's tensile strength, 0.2% yield strength, percent elongation and Brinell hardness number and are listed in Mathematical Model Set IV.

MATHEMATICAL MODEL SET III - SERIES 2A

EQUATIONS

TENSILE STRENGTH = 47,050.7 + 39,250.9 (T.C.) - 32,379.7 (% Si) - 16,249.0 (% Mn) - 2,920.4 (% Ni) - 5424.0 (% Mo) + 59,811.2 (% Mg) ....(11)

$R_{(11)} = 0.658$ $\sigma_{e(11)} = 7,562$

0.2% YIELD STRENGTH = 77,415.6 - 5.55 (T.C.) + .697 (% Si) + 5.7 (% Mn) - .48 (% Ni) + 2.34 (% Mo) + .046 (% Mg)......................(12)

$R_{(12)} = 0.508$ $\sigma_{e(12)} = 6,220$

PERCENT ELONGATION = 3.48 - 0.017 (T.C.) - 0.002 (% Si) + 0.00092 (% Mn) -0.00645 (% Ni) + 0.021 (% Mo) + 0.172 (% Mg).................(13)

$R_{(13)} = 0.439$ $\sigma_{e(13)} = 1.325$

BRINELL HARDNESS NUMBER = 191.6 + 28.3 (T.C.) - 15.8 (% Si) + 17.7 (% Mn) + 15.1 (% Ni) + 58.9 (% Mo) - 355.9 (% Mg)...................(14)

$R_{(14)} = 0.867$ $\sigma_{e(14)} = 7.04$

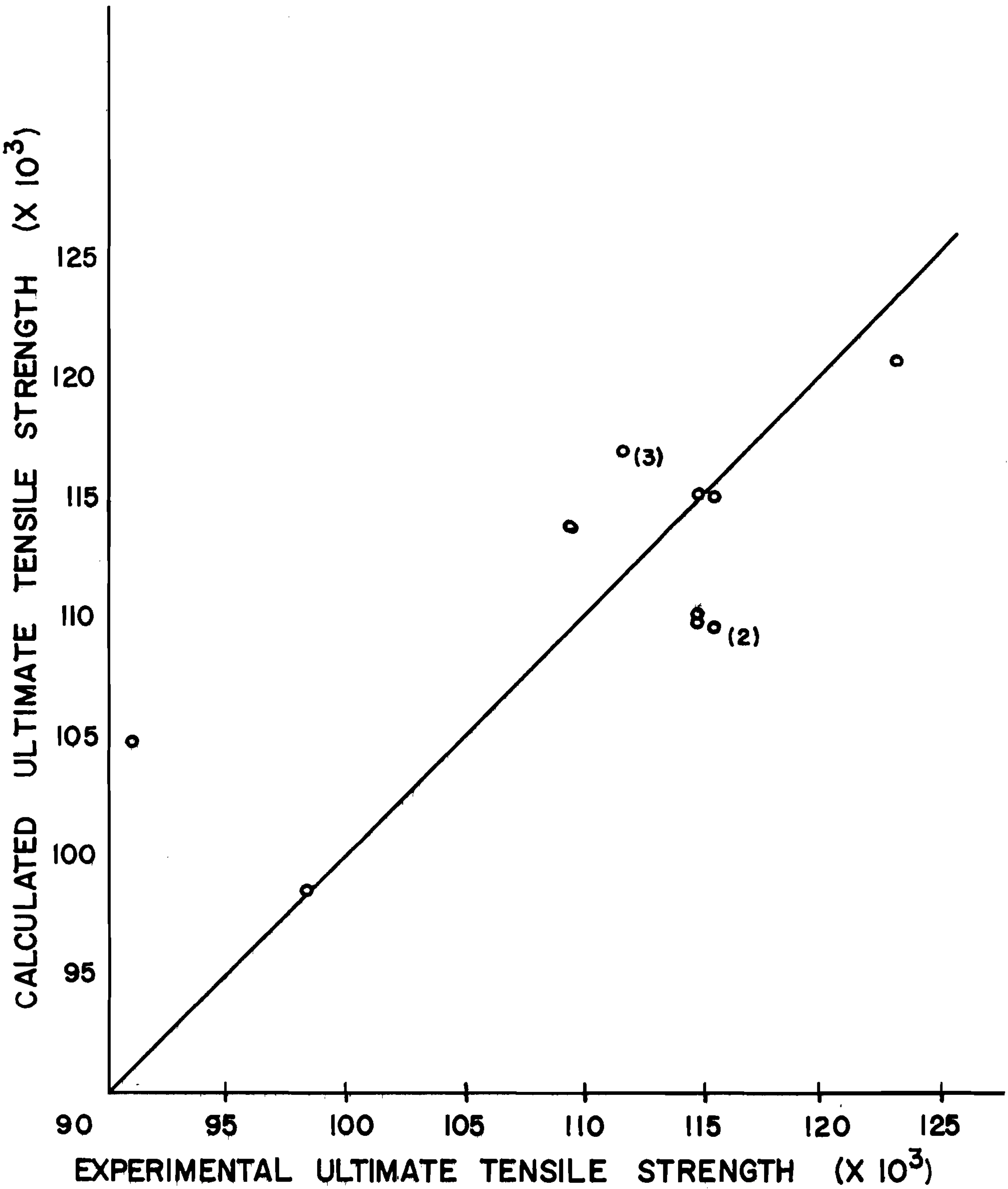

FIGURE 21 EXPERIMENTAL ULTIMATE TENSILE STRENGTH VERSUS CALCULATED ULTIMATE TENSILE STRENGTH FOR SERIES 2A- AS CAST MECHANICAL PROPERTIES

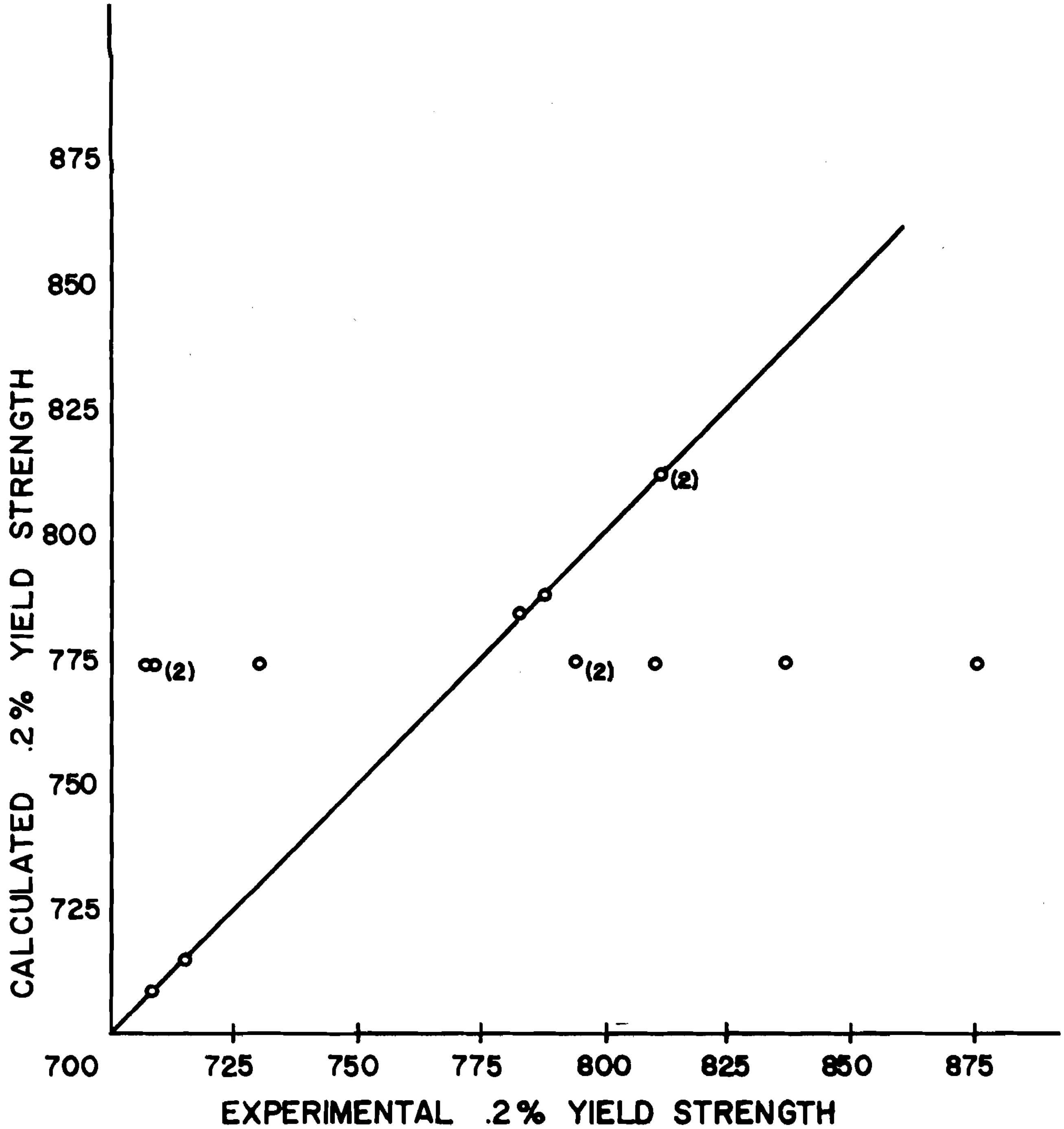

FIGURE 22 EXPERIMENTAL .2% YIELD STRENGTH VERSUS CALCULATED .2% YIELD STRENGTH FOR SERIES 2A-AS CAST MECHANICAL PROPERTIES

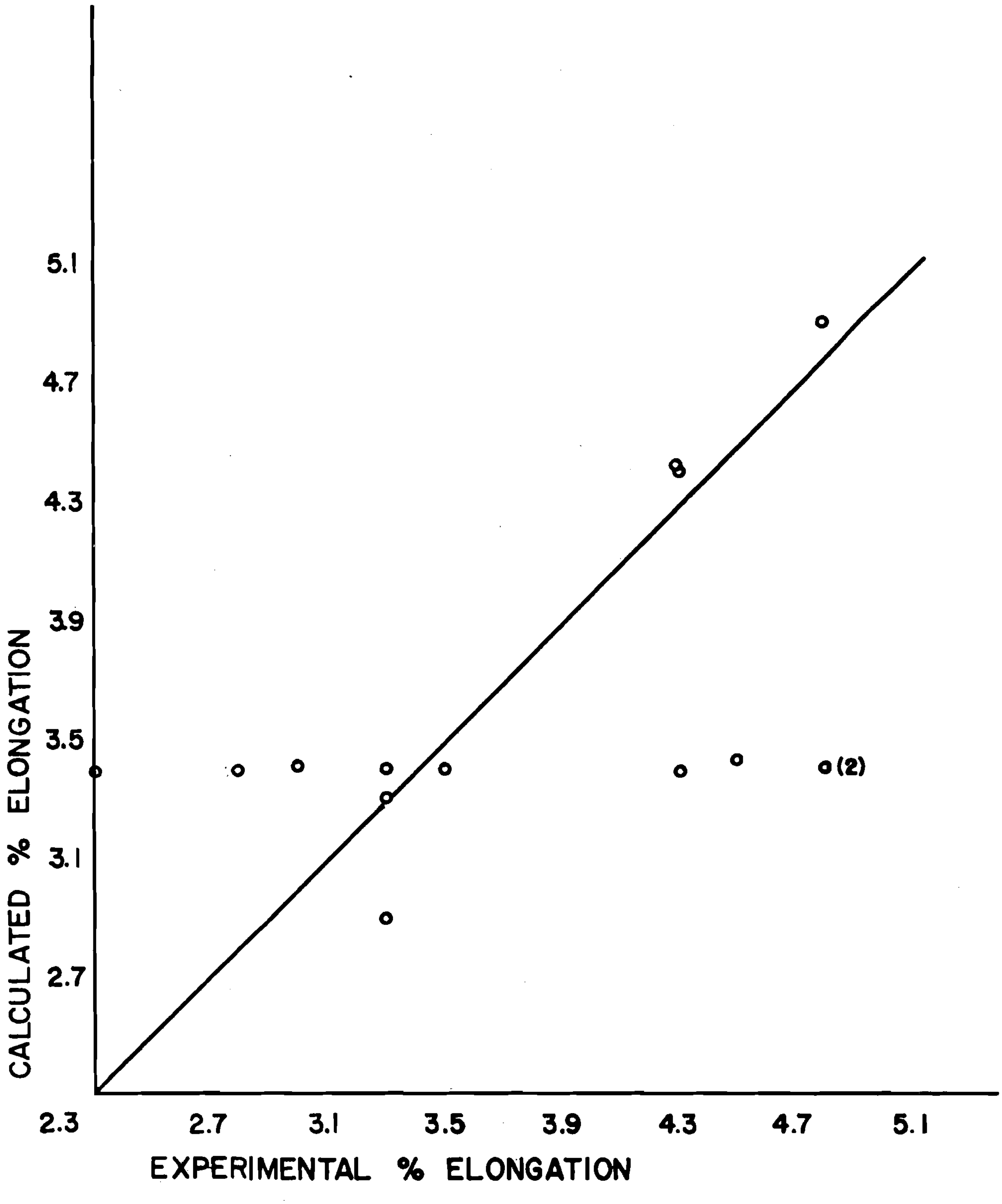

FIGURE 23 EXPERIMENTAL % ELONGATION VERSUS CALCULATED % ELONGATION FOR SERIES 2A-AS CAST MECHANICAL PROPERTIES

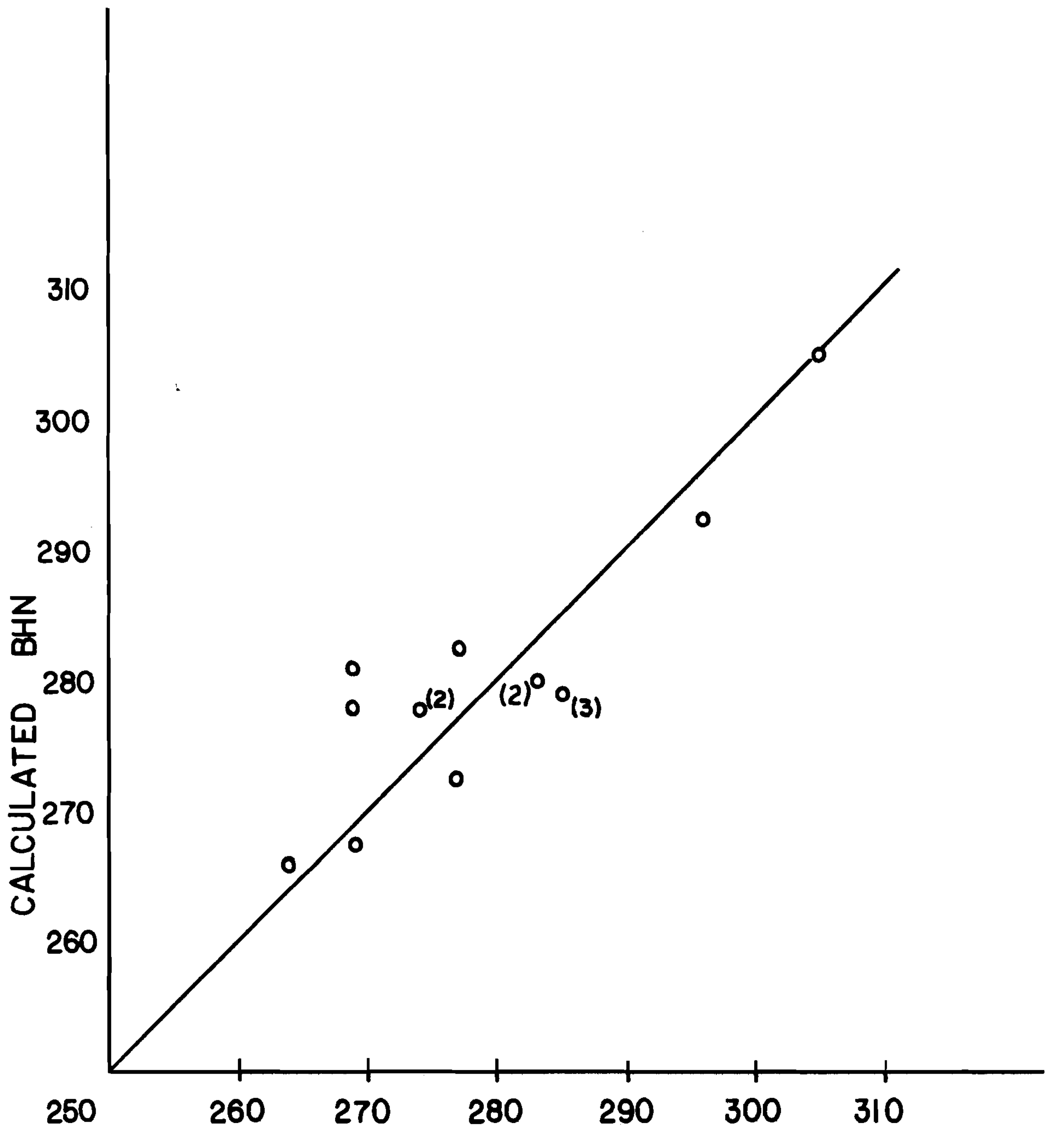

FIGURE 24 EXPERIMENTAL BHN VERSUS CALCULATED BHN FOR SERIES 2A- AS CAST MECHANICAL PROPERTIES

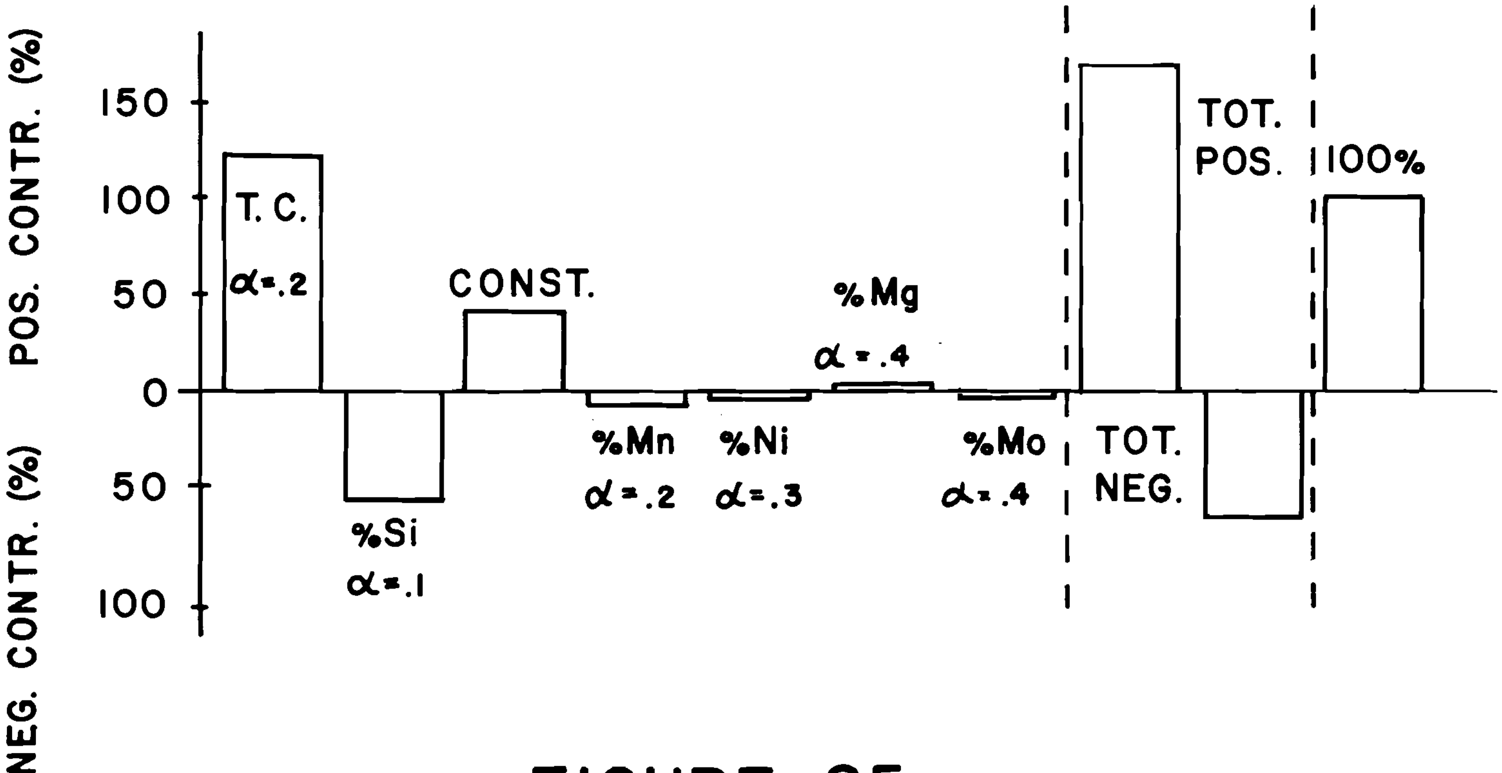

FIGURE 25

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE

ULTIMATE TENSILE STRENGTH

OF THE SERIES 2-A AS-CAST MECHANICAL PROPERTIES

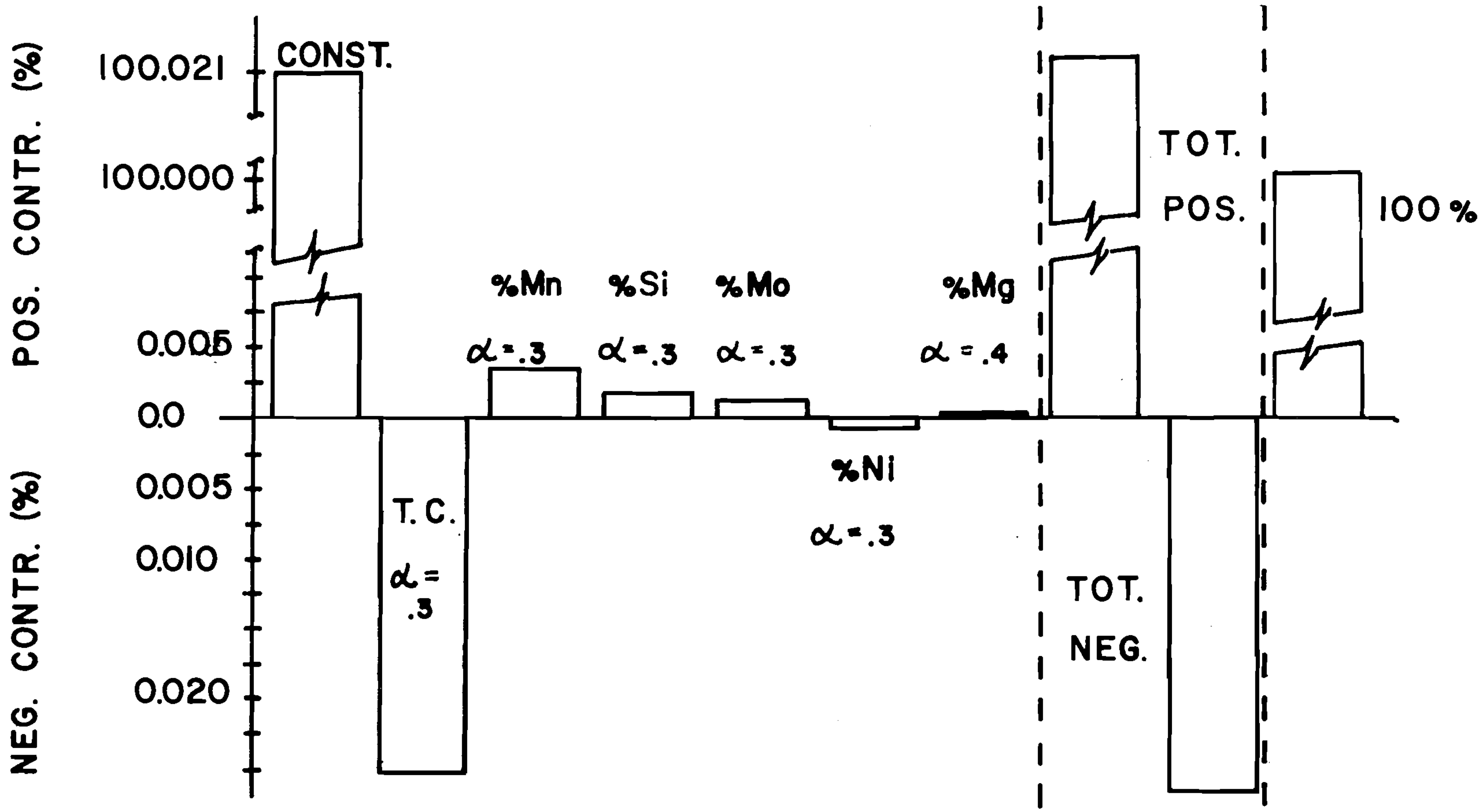

FIGURE 26

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE

0.2 % YIELD STRENGTH

OF THE SERIES 2-A AS-CAST MECHANICAL PROPERTIES

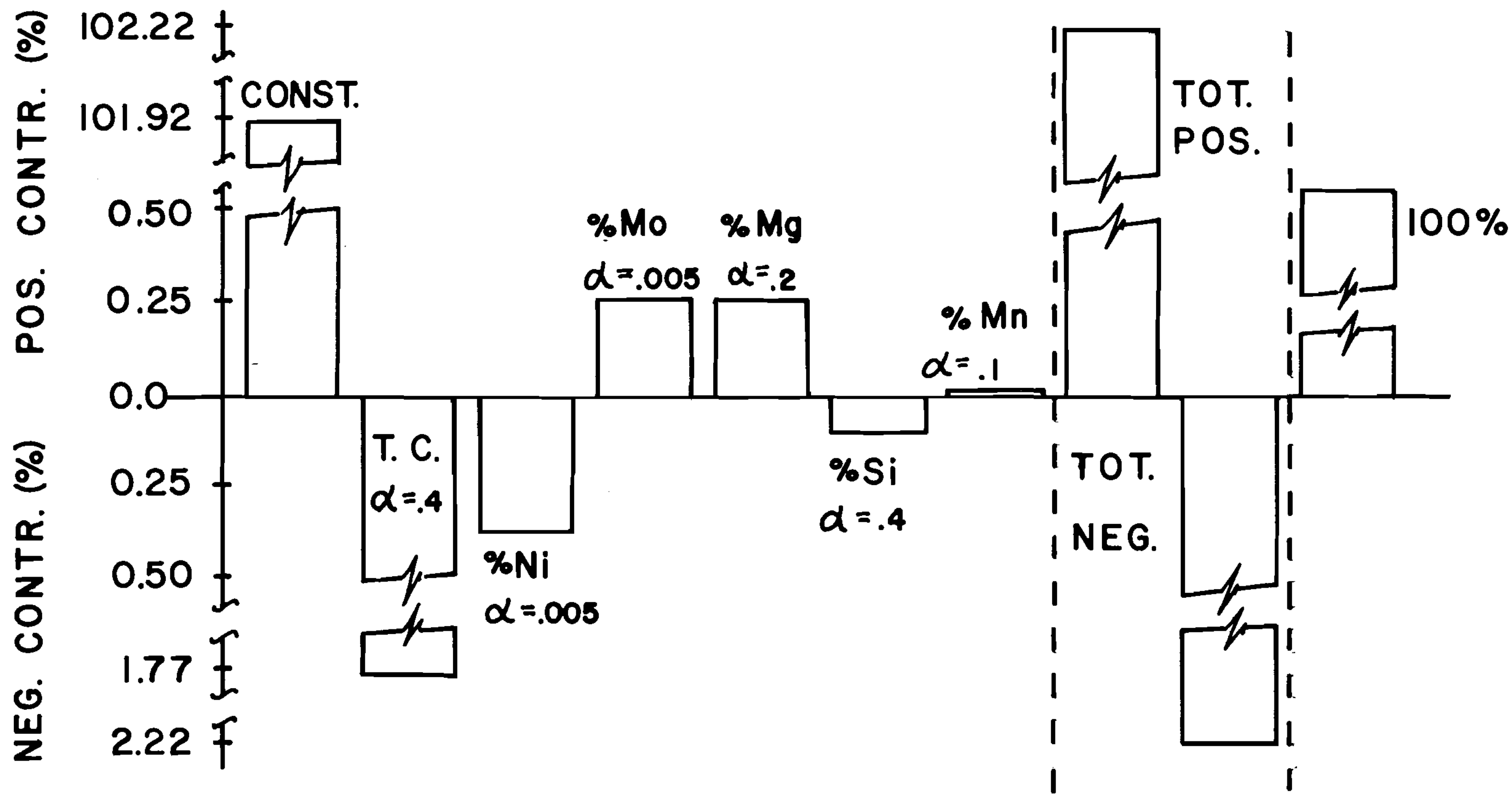

FIGURE 27

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE

PERCENT ELONGATION

OF THE SERIES 2-A AS-CAST MECHANICAL PROPERTIES

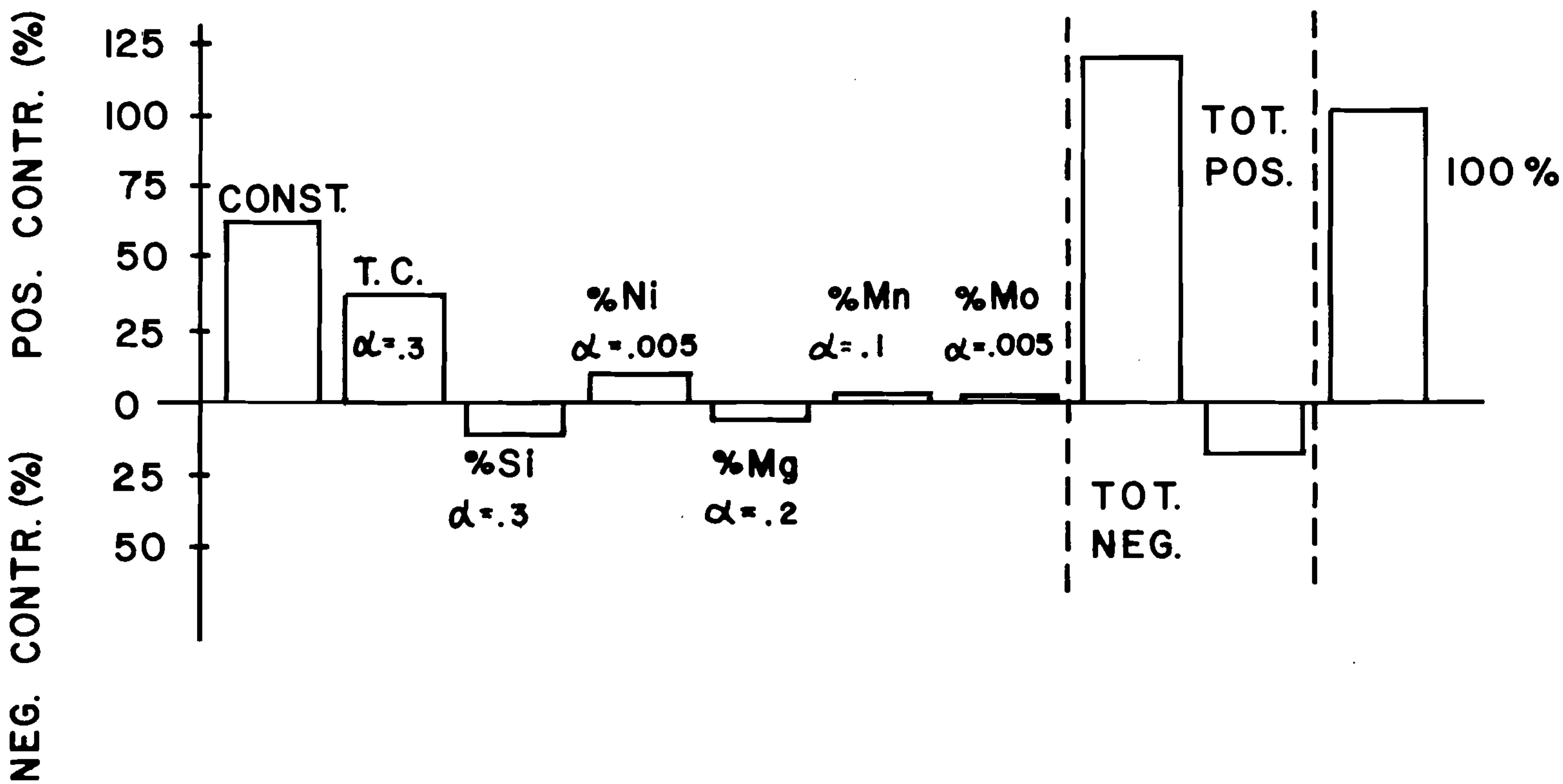

FIGURE 28

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE BRINELL HARDNESS OF THE SERIES 2-A AS-CAST MECHANICAL PROPERTIES

TABLE 7 QUANTATIVE RESULTS OF INITIAL TENSILE, YIELD, ELONGATION AND HARDNESS EQUATIONS

SERIES 2A

AS CAST DATA		TENSILE STRENGTH		0.2% YIELD STRENGTH		PERCENT ELONGATION		BRINELL HARDNESS	
IND. VAR.	MEAN VALUE	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.
T. C.	3.56	139,733	123.02	-19.76	-0.0255	-0.0605	-1.772	100.748	35.95
% Si	1.96	-63,464	-55.86	1.37	0.0018	-0.0039	-0.115	-30.968	-11.05
% Mn	0.458	-7,442	-6.55	2.61	0.0034	0.0004	0.012	8.106	2.89
% Ni	1.766	-5,157	-4.54	-0.85	-0.0011	-0.0114	-0.334	26.666	9.52
% Mo	0.0426	-231	-0.205	0.099	0.0013	0.0009	0.264	2.509	0.89
% Mg	0.05173	3,094	2.72	0.024	0.0002	0.0089	0.260	-18.411	-6.57
CONST.		47,051	41.42	77,415.6	100.0210	3.4800	101.920	191.600	68.37
MEAN MECH. PROPERTY		113,583	100.00	77,399.1	100.00	3.4144	100.000	280.250	100.00

MATHEMATICAL MODEL SET IV - SERIES 2B

EQUATIONS

TENSILE STRENGTH = 117,236 + 9,785 (T.C.) - 15,498 (% Si)
+ 12,699 (%Mn) - 708 (% Ni) - 2,426 (% Mo)
+ 86,524 (% Mg)...............................(15)

$R_{(15)} = 0.984$ $\sigma_{e_{(15)}} = 1,067$

0.2 PERCENT YIELD STRENGTH = 131,908 - 23,213 (T.C.) + 2,381 (% Si)
+ 22,889 (% Mn) + 7,637 (% Ni)
+ 89,986 (% Mo) $\pm$ 125,130 (% Mg).....(16)

$R_{(16)} = 0.999$ $\sigma_{e_{(16)}} = 853$

PERCENT ELONGATION = - 9.4 + 5.6 (T.C.) - 2.2 (% Si) - 1.5 (% Mn)
- 1.2 (% Ni) - 8.3 (% Mo) + 13.3 (% Mg).......(17)

$R_{(17)} = 0.999$ $\sigma_{e_{(17)}} = 0.08$

BRINELL HARDNESS NUMBER = 517.2 - 15.6 (T.C.) - 85.9 (% Si) + 3.5 (% Mn)
- 4.3 (Ni) 187.9 (% Mo) - 263.9 (% Mg)...(18)

$R_{(18)} = 0.999$ $\sigma_{e_{(18)}} = 0.02$

IV. D. 2. Statistical Significance

Equations 15-18 had the highest correlation coefficients achieved during the entire investigation and all four were significant at the 0.001, confidence level.

The plotbacks of these four models are shown in Figures 29-32 and visibly illustrate the high value of each correlation coefficient.

In addition, Figures 33-36 identify the level of significance of each independent variable contained in equations 15-18. Twenty-three (23) out of the total twenty-four (24) elemental variables in these four (4) models are statistically significant from the 0.2 confidence level down to the 0.0005 confidence level. The remaining variable was significant at the 0.3 confidence level.

IV. D. 3. Metallurgical Significance

Qualitatively, equation 15 indicates that tensile strength of the normalized ductile cast iron increases with additions of carbon, manganese and magnesium and decreases with additions of silicon, nickel and molybdenum. Equation 16 shows that the yield strength tends to increase with silicon, manganese, nickel, molybdenum and magnesium additions and will be reduced with carbon additions. Equation 17 indicates that while carbon and magnesium enhance the percent elongation, silicon, manganese, nickel and molybdenum tend to decrease this property. Finally, equation 18 shows that manganese, nickel and molybdenum additions increase the Brinell hardness number while carbon, silicon and magnesium decrease this property.

Figure 33-36 and Table 8 show the mean quantitative contributions of each independent elemental variable towards the magnitude of the dependent mechanical properties. Further examination of these figures indicates that all the elemental variables used in these models, except the silicon in equation 16, can be trusted due to the fact that their α values are 0.2 or less.

Thus, this last series of mathematical models are the most significant ones derived during this investigation and could be experimented with in the design of ductile cast iron alloys with improved mechanical properties.

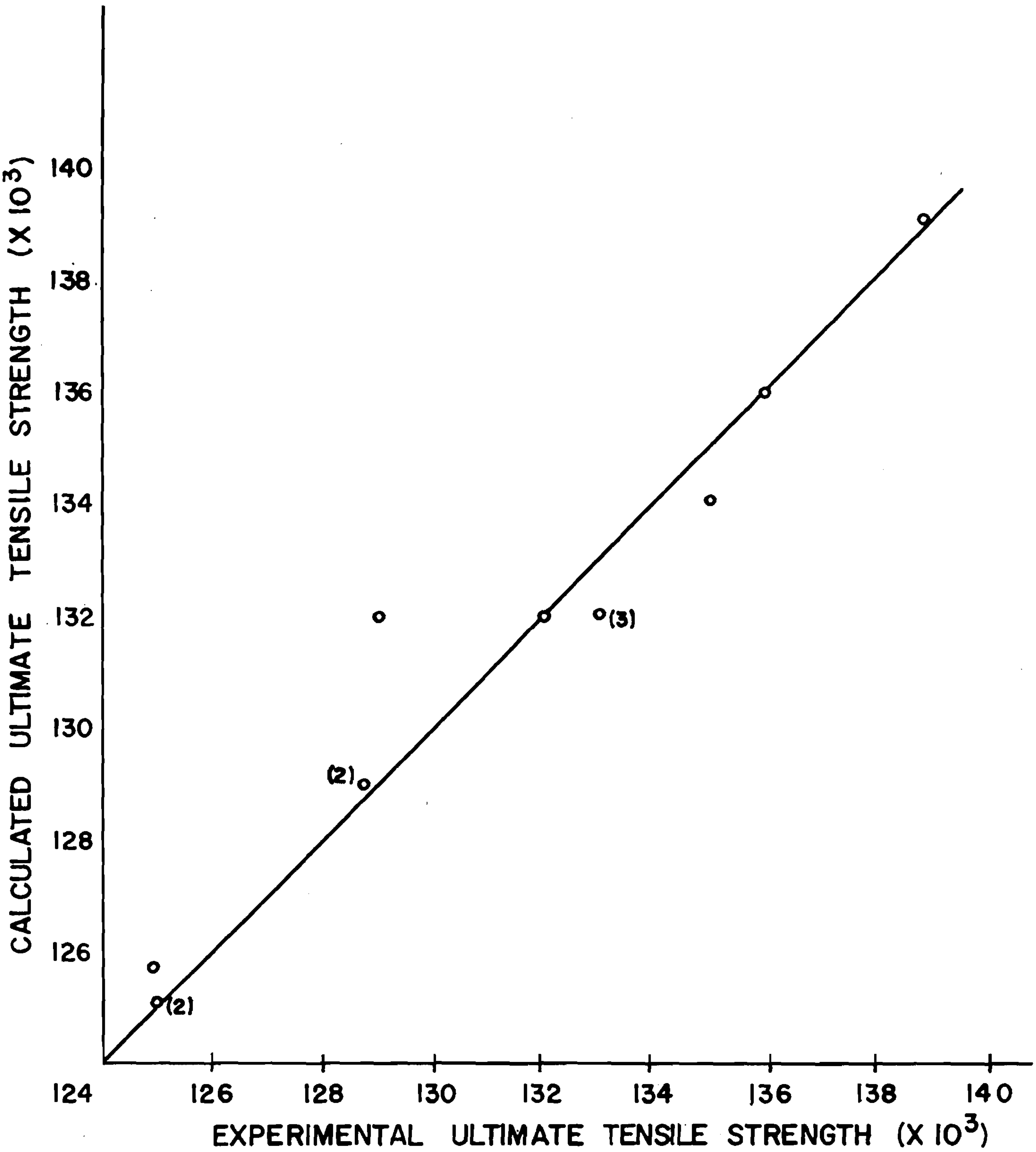

FIGURE 29 EXPERIMENTAL ULTIMATE TENSILE STRENGTH VERSUS CALCULATED ULTIMATE TENSILE STRENGTH FOR SERIES 2B-NORMALIZED MECHANICAL PROPERTIES

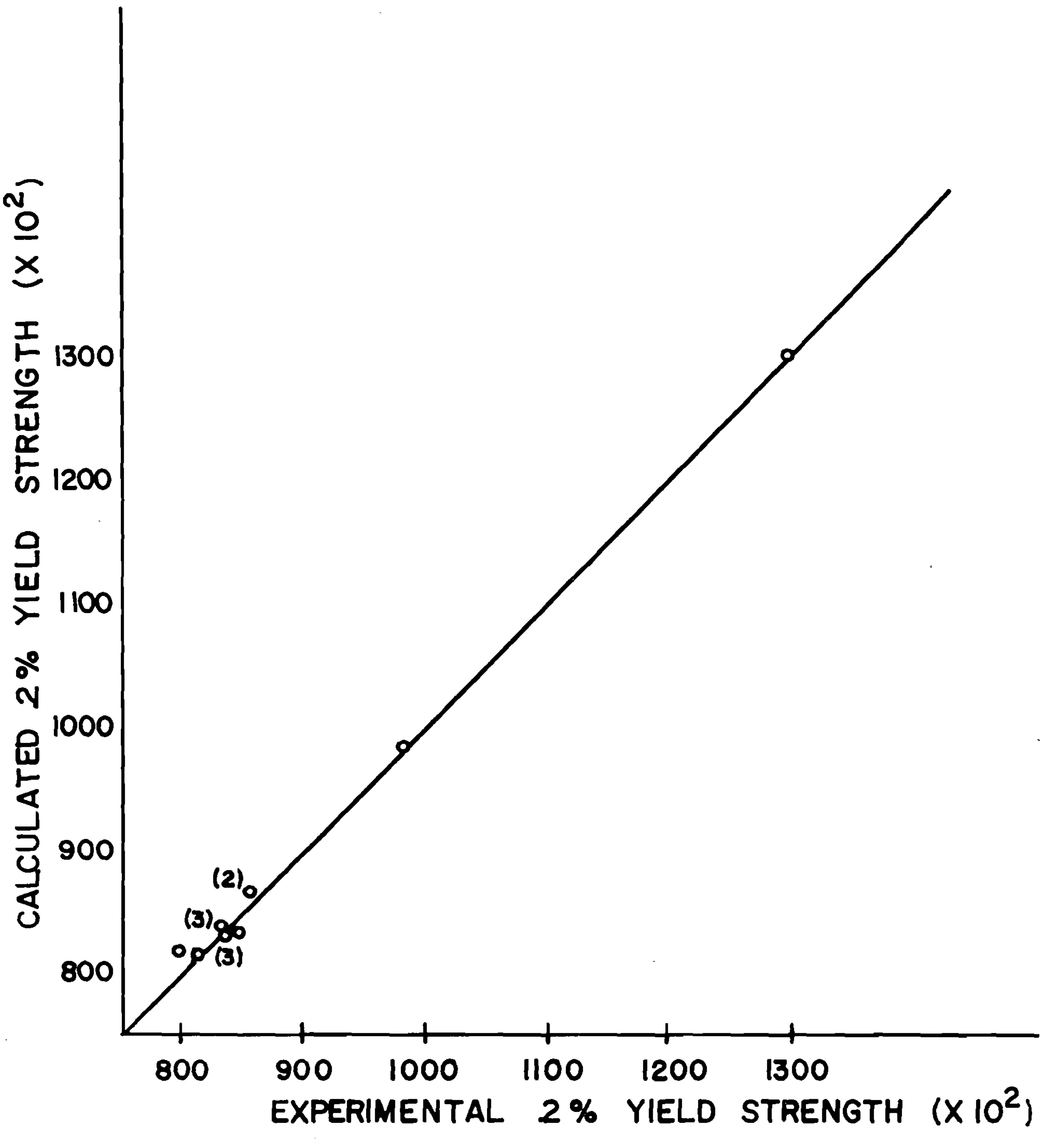

FIGURE 30 EXPERIMENTAL .2% YIELD STRENGTH VERSUS CALCULATED .2% YIELD STRENGTH FOR SERIES 2B- NORMALIZED MECHANICAL PROPERTIES

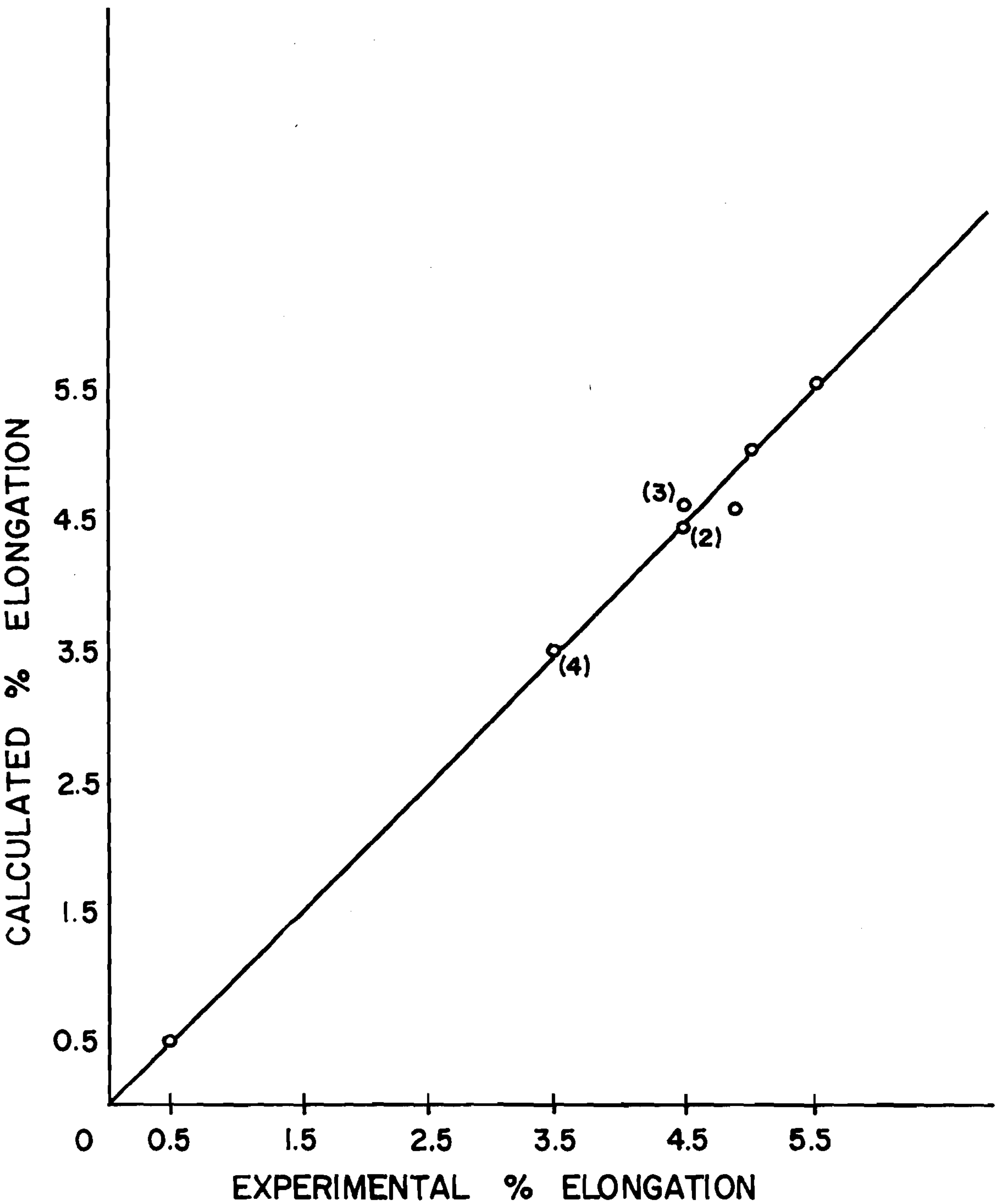

FIGURE 31 EXPERIMENTAL % ELONGATION VERSUS CALCULATED % ELONGATION FOR SERIES 2B-NORMALIZED MECHANICAL PROPERTIES

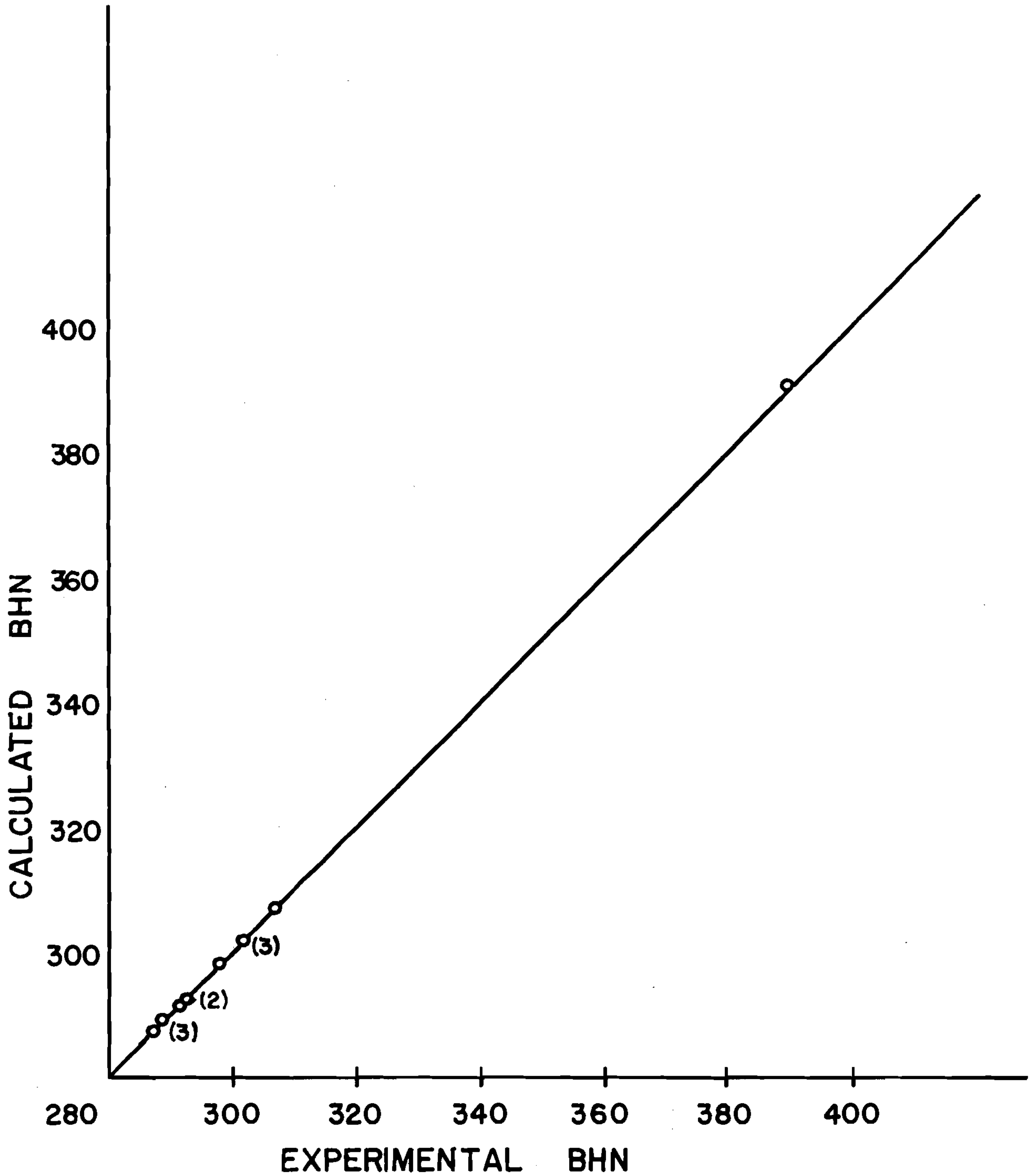

FIGURE 32 EXPERIMENTAL BHN VERSUS CALCULATED BHN FOR SERIES 2B-NORMALIZED MECHANICAL PROPERTIES

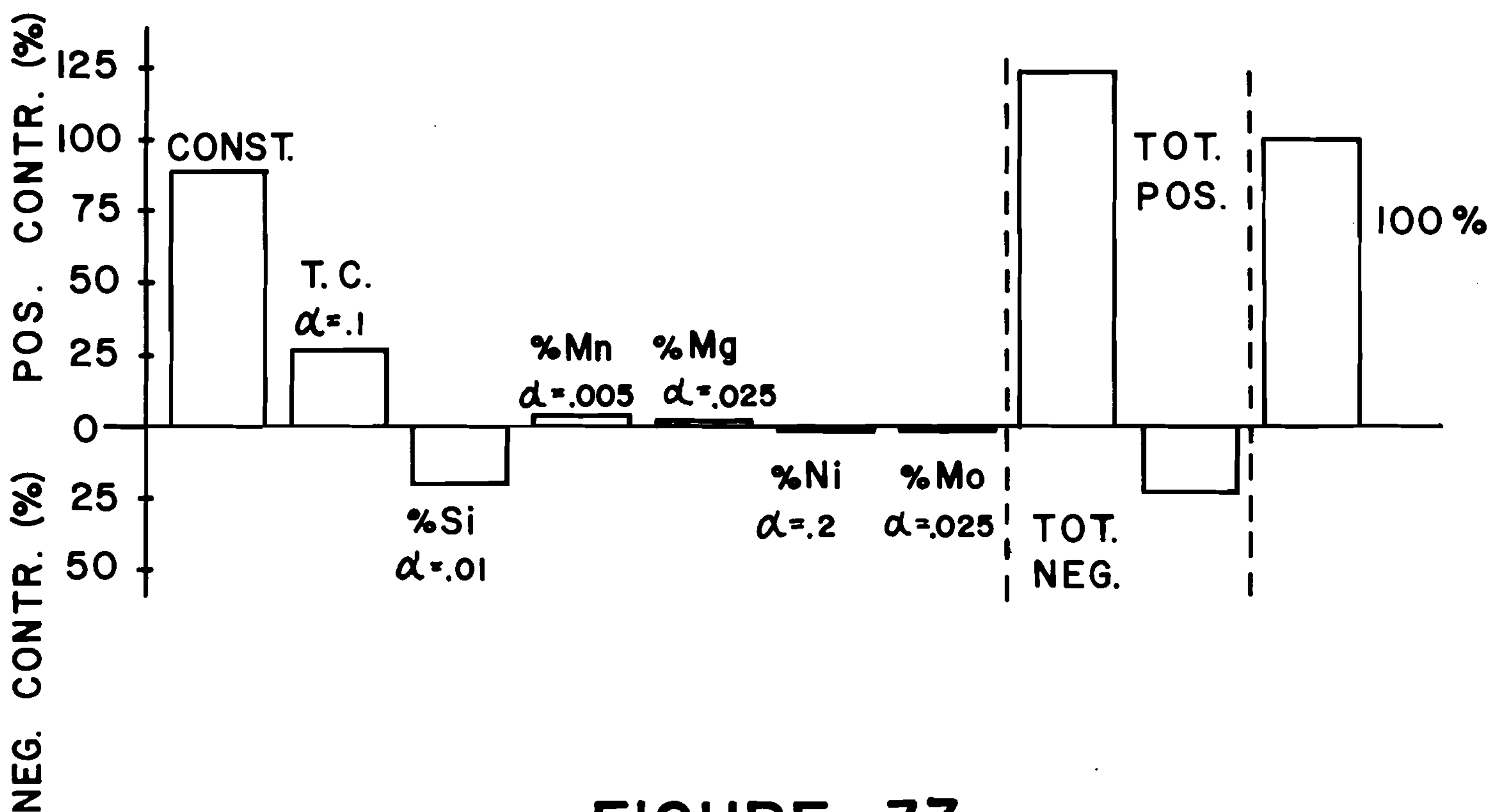

FIGURE 33

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE

ULTIMATE TENSILE STRENGTH

OF THE SERIES 2-B AVERAGE NORMALIZED MECHANICAL PROPERTIES

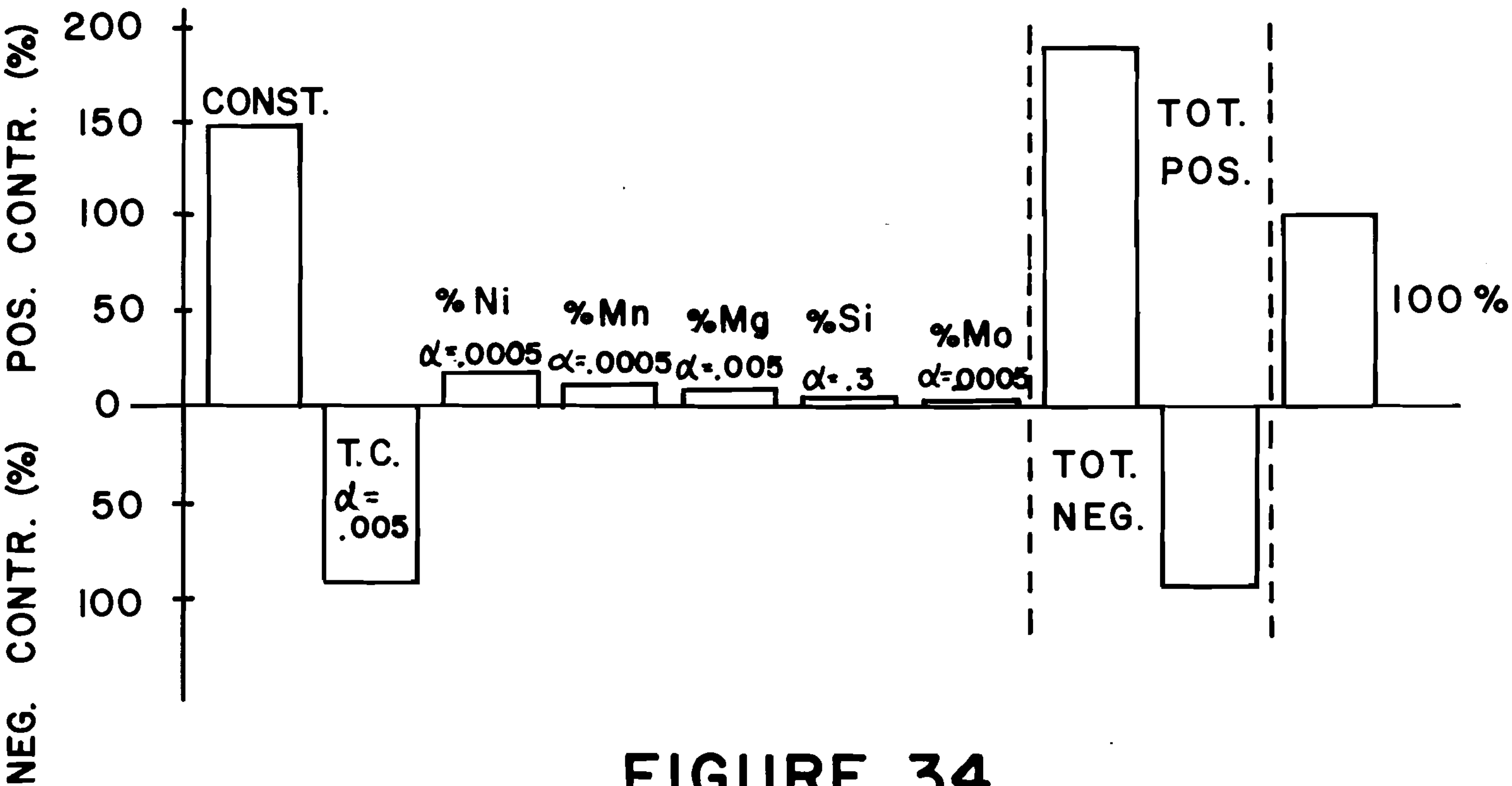

FIGURE 34

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE

0.2 % YIELD STRENGTH

OF THE SERIES 2-B AVERAGE NORMALIZED MECHANICAL PROPERTIES

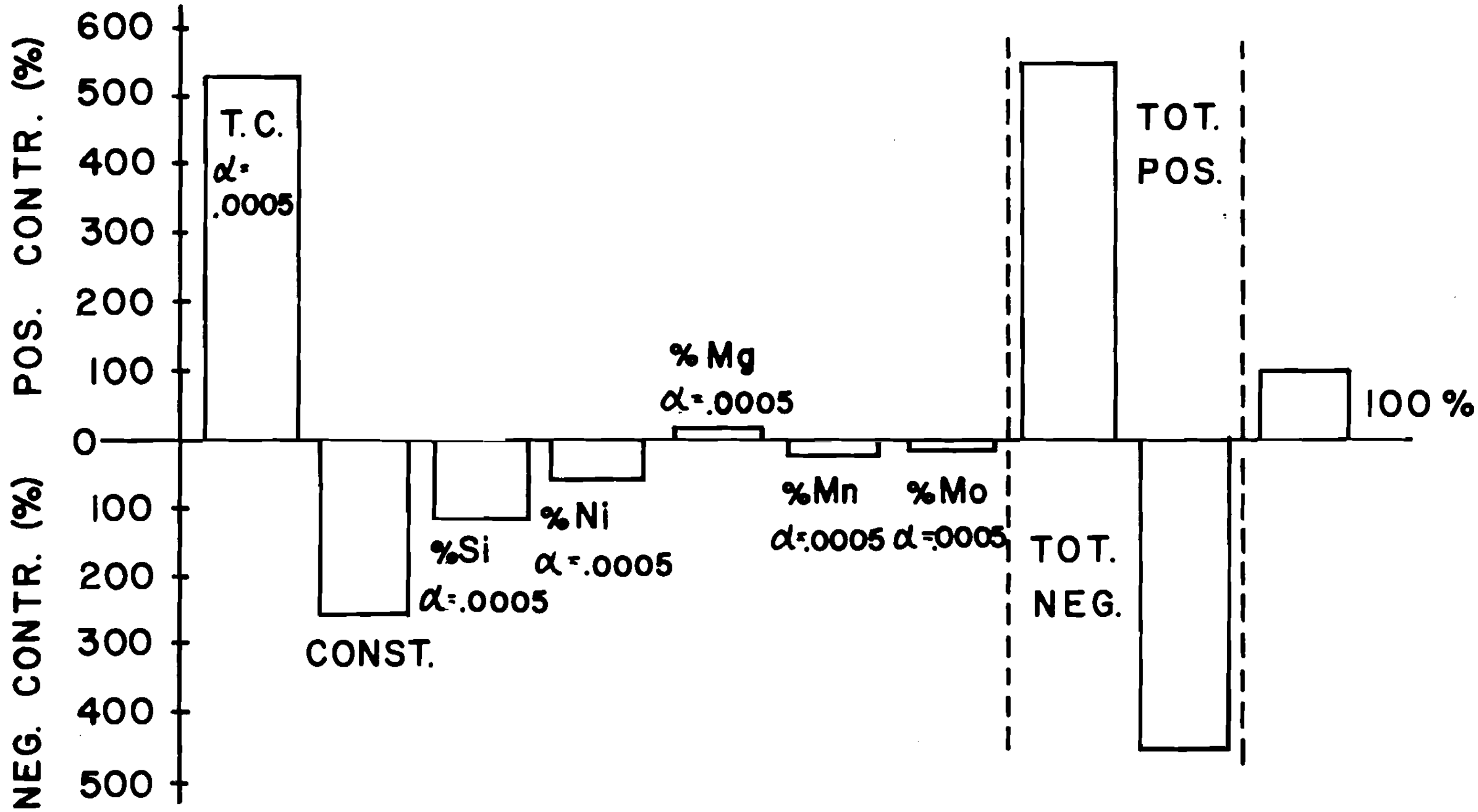

FIGURE 35

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE

PERCENT ELONGATION

OF THE SERIES 2-B AVERAGE NORMALIZED MECHANICAL PROPERTIES

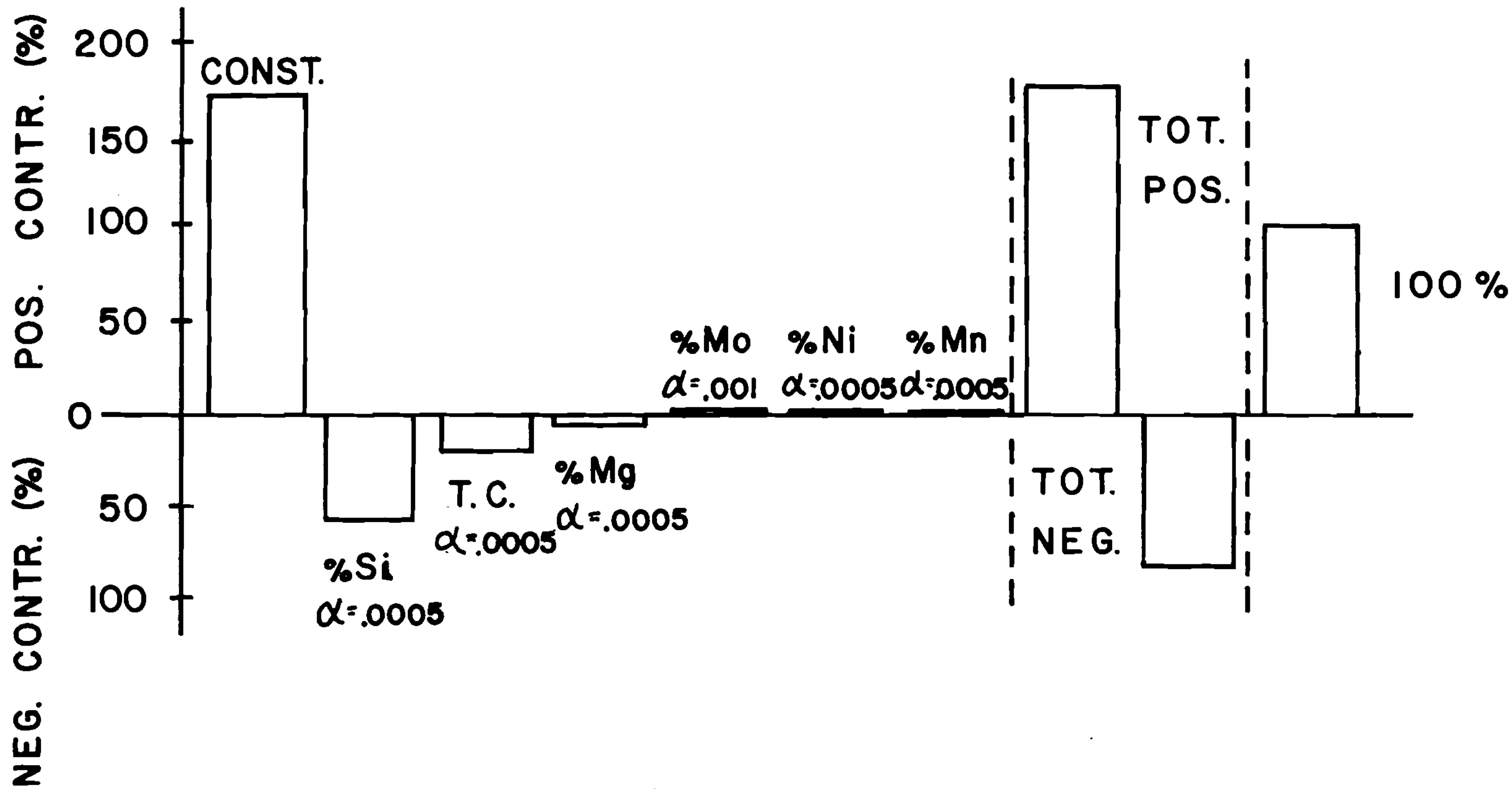

FIGURE 36

PERCENT CONTRIBUTIONS OF THE INDEPENDENT VARIABLES TO THE

BRINELL HARDNESS

OF THE SERIES 2-B AVERAGE NORMALIZED MECHANICAL PROPERTIES

TABLE 8 QUANTITATIVE RESULTS OF INITIAL TENSILE, YIELD, ELONGATION AND HARDNESS EQUATIONS

SERIES 2B

VERAGE NORMALIZED ATA		TENSILE STRENGTH		0.2% YIELD STRENGTH		PERCENT ELONGATION		BRINELL HARDNESS	
IND. VAR.	MEAN VALUE	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.	MEAN CONTR.	PERCENT CONTR.
C.	3.56	34,834	26.67	-82,638	-93.68	19.94	531.34	-55.54	-18.71
Si	1.96	-30,376	-23.25	4,667	5.29	-4.31	-114.93	-168.36	-56.72
Mn	0.458	5,816	4.45	10,483	11.88	-0.69	-18.31	1.60	0.54
Ni	1.766	-1,250	-0.96	13,487	15.29	-2.12	-56.48	7.59	2.56
Mo	0.0426	-103	-0.08	3,833	4.35	-0.35	-9.44	8.00	2.70
Mg	0.05173	4,476	3.43	6,473	7.34	+0.69	18.34	-13.65	-4.59
ONST.		117,236	89.74	131,908	149.53	9.40	-250.53	517.20	174.23
EAN MECH. ROPERTY		130,633	100.0	88,213	100.0	3.74	100.0	296.85	100.0

V. UTILIZATION OF EQUATIONS

The statistically and metallurgically significant mathematical models can be used to design improved cast shell alloys and thus replace a great deal of "guess-work" and "rule of thumb" techniques currently being implemented.

The equations could also be maximized or minimized for any variable by proper adjustment of the other variables. Several limitations should be imposed, however, and are as follows:

1. The independent variables should be similar to those used in generating these data that are evaluated herein;

2. Extrapolation can be permitted to a small degree; and

3. Only the more significant variable contributors should be varied, i.e., only those whose α's are 0.20 or less.

The use of reliable, statistically derived equations in research and development fields is obvious. They allow better qualitative and quantitative judgments to be made. They can also be used as tools to guide experimental and theoretical studies in the effort to learn more about metal systems.

VI. CONCLUSIONS

Incomplete fragmentation data resulted in the redirection of this project towards an implementation of a scientific analysis of factors affecting the mechanical properties of ductile cast iron alloys. The Series 1 mathematical models involving tensile strength, 0.2% yield strength, percent elongation, percent reduction in area and Brinell hardness number as the dependent variables and four (4) independent, microstructural variables proved inconclusive due to insufficient data sets, but, established a good foundation for future investigations. The Series 2 equations involving all but the percent reduction in area variable and six (6) independent, elemental variables proved to be significant, especially in the as normalized, Series 2B models. Statistically, equations 15, 16, 17 and 18 were significant at the 0.001 confidence level, or less, and twenty-three (23) out of twenty-four (24) elemental variables in these four (4) models are significant from the 0.2 confidence level down to the 0.0005 confidence level. Metallurgical significance of the last four(4) equations can be based on the following criteria of judgment, i.e.,

1. Carbon and silicon are graphitizers and ferritizers and should decrease strength properties and increase ductility properties;

2. Nickel and magnesium are ferrite strengtheners and should increase strength while decreasing ductility; and

3. Manganese and molybdenum are pearlite stabilizers which should also increase strength and decrease ductility.

Thus, seventeen (17) out of the twenty-four (24) independent, elemental variables, or 71%, are in agreement with metallurgical theory.

VII. RECOMMENDATIONS

Since this investigation was based on a limited number of reliable data sets, it is recommended that it be continued and expanded in scope during the next year.

VIII. ACKNOWLEDGEMENTS

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